ERGONOMICS CONSIDERATIONS IN IT-ENABLED COMPUTER-AIDED DESIGN FOR DISCRETE MANUFACTURED PRODUCTS

by

Adaeze Florence Nwaigwe

BEngr., Electrical Engineering, University of Nigeria, Nsukka, 1993

MSc, Electrical Engineering, University of Lagos, 1996

MS, Industrial Engineering, University of Pittsburgh, 2002

Submitted to the Graduate Faculty of

School of Engineering in partial fulfillment

of the requirements for the degree of

Doctor of Philosophy

University of Pittsburgh

2005

UNIVERSITY OF PITTSBURGH

SCHOOL OF ENGINEERING

This dissertation was presented

by

Adaeze Florence Nwaigwe

It was defended on

November 15, 2005

and approved by

Bart Nnaji, PhD, Professor, Industrial Engineering Department

Harvey Wolfe, PhD, Professor, Industrial Engineering Department

Rory Cooper, PhD, Professor, Bioengineering Engineering Department

Mary Sacre, PhD, Associate Professor, Industrial Engineering Department

Rakie Cham, PhD, Assistant Professor, Bioengineering Engineering Department

Dissertation Director: Bart Nnaji, PhD, Professor, Industrial Engineering Department

ERGONOMICS CONSIDERATIONS IN IT-ENABLED COMPUTER-AIDED DESIGN FOR DISCRETE MANUFACTURED PRODUCTS

Adaeze Florence Nwaigwe, PhD

University of Pittsburgh, 2005

Despite great advances in the field of ergonomics, its integration into the conceptual stage of computer-aided product design remains limited. In order that a product be designed for safety and comfort, it is essential that pertinent ergonomic principles be imposed as design constraints during design conceptualization. Further, it is vital that these constraints be propagated to downstream design activities so that they can be considered along with other design constraints such as manufacturing and assembly, in deriving design alternatives and subsequently in determining the outcome of the final product. This should enable the design of safer and more comfortable products, minimize design iterations that often result from ergonomic violations, reduce design cycle time and hence minimize product lifecycle cost.

This work proposes a computer-aided design methodology for the conceptual design of discrete products using an expert system approach. The feasibility of the methodology is tested by implementing it in a Java-based software application and applied to the design of a wheelchair seating system. The performance of the proposed method is compared to that of the current method. Results obtained show that the new method outperforms the current method in terms of design cycle time. The new method also proves very helpful in fast tracking designers to necessary ergonomic design data.

DESCRIPTORS

Algebraic Constraint Representation

CAD

Computer-Aided Design

Computer-Aided Product Design

Conceptual design

Design

Ergonomics

Ergonomic Principles

Ergonomic Rules

Extensible Markup Language

Wheelchair Seating System

XML

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACKNOWLEDGEMENTS

To God almighty for his enduring mercies and for his strength during the course of my graduate studies. To my advisor, Dr Bart Nnaji and my committee members for their guidance during the course of my dissertation.To my husband, for his support and guidance. To my little ones, Nnenna and Ify, for their endurance and understanding. To my parents and extended family for their undying support and belief in me. To the staff of Industrial Engineering department, Minerva, Lisa and Richard, and the members of the NSF I/UCR Center for e-design, for their help in so many ways. God bless you all.

1.0 INTRODUCTION

The application of computers to the design of discrete manufactured products for ergonomics has seen tremendous improvements in the past decade. However, these improvements have been focused on improving tools for processes involved in the evaluation stage of computer-aided design (CAD). Little advancement has been made towards building CAD tools that impose ergonomic considerations on design concepts. Early imposition of design constraints should improve the CAD process by reducing the number of design iterations that otherwise would be necessary and therefore shortening design cycle time. Further, introducing ergonomic considerations early in the design process should promote the likelihood of them being taken into account in detailed design processes. The CAD process is shown in figure 1-1.

In this dissertation, a computer-aided ergonomic tool is developed for incorporating considerations for physical ergonomics at the conceptual stage of computer-aided product design. The tool, which uses an expert system approach, addresses the following ergonomic considerations - contact stress, tissue distortion, shear and friction forces, static load, forceful exertions, frequency of body motion, awkward posture, clearance, vibration, temperature, and moisture exposure. The tool is written in Java object-oriented programming language and is designed to run on a Microsoft Operating System and on the World Wide Web (WWW). This research tests the hypothesis that the tool developed will indeed reduce design cycle time. This hypothesis is tested in the design of a wheelchair seating system. To illustrate the generalization of the methodology presented, its application to the design of a pen is discussed.

Conceptual design has a major impact in defining the nature and amount of work required during the detailed design phase and other subsequent activities such as manufacturing. When a design is poorly conceived, such a design cannot be compensated for by a good detailed design, since the design direction and possibly scope, has already been laid down during the conceptual stage. In other words, the detailed design phase merely works within the scope defined during the conceptual stage. In fact, it is well established that about 75% of the entire cost of a product is committed during the design phase. This commitment also extends to design changeability, that is, the ability to change or influence the final product design. [(1)*]

The science of ergonomics is the key to designing human-centered products. The discipline studies human characteristics and then systematically applies their limitations and capabilities to the design of products/systems, workplaces, and the environment. Its fundamental goal is that all man-made tools, devices, equipment, machines, and environments should advance directly or indirectly, the safety, well-being, and performance of all mankind. Success is then measured by improved productivity, efficiency, safety, acceptance of the resultant system design[2] and ultimately improved quality of human life.

A class of injuries occurring during person-product interaction is biomechanical injuries. These injuries are usually caused by the infliction of excessive forces and moments on the body. Some well known biomechanical injuries are musculoskeletal disorder (MSDs). The United States (U.S.) Department of Labor defines MSDs as injuries or disorders of the muscles, nerves, tendons, joints, cartilage, and spinal discs.[3] These injuries develop over a period of time and their cause and effect are not directly obvious.

From the foregoing, it can be seen that integrating constraints of ergonomics into the conceptual stage of CAD design is of great significance. If a design warrants costly changes in

[*] Parenthetical references placed superior to the line of text refer to the bibliography.

order to satisfy the rules of ergonomics, a designer may well opt out of making those changes. The result may be products whose features are incompatible with the physical and mental needs of its users. Tools that support timely integration of ergonomic considerations are therefore required.

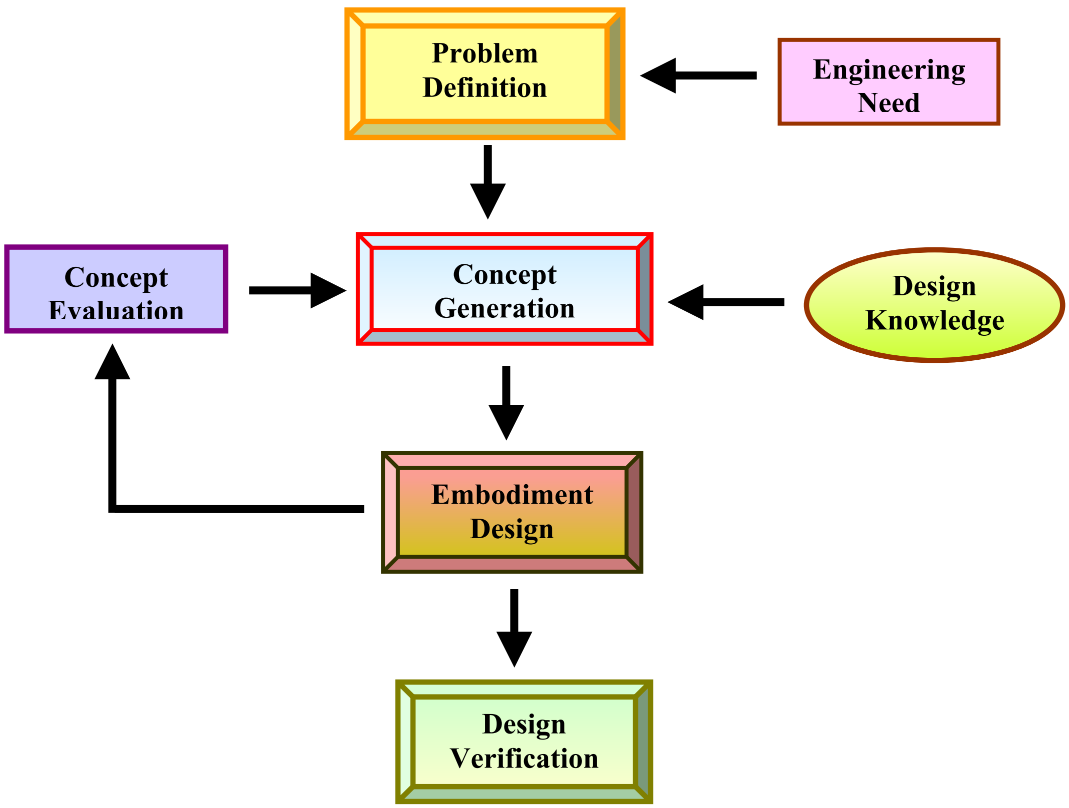

Figure 1-1 The computer-aided design process

1.1 RESEARCH OBJECTIVES

The primary objective of this dissertation is to test the hypothesis that the proposed methodology reduces design cycle time for discrete products and in a CAD environment.

1.2 CONTRIBUTIONS

Compared to the current method, the computer-aided ergonomic tool developed in this work proved superior at improving the CAD process by generating ergonomic constraints, much faster. This work is premier in applying the concept of group technology to the design of products for ergonomics.

1.3 METHOD

The first step towards meeting the objective of this dissertation is the construction and computer implementation of the methodology to be tested. The proposed methodology, shown below, has three components:

1. Categorization of discrete products for ergonomic design: Categorization of objects allows for efficient interaction with these objects in terms of access and retrieval of information and therefore, helps save time. A classification and coding system which

uses Boolean logic, is presented for grouping products according to the similarity they share for ergonomic considerations which is dependent on the functions users of the product will perform on them. The latter are known as product functions.[4] For example, to drink from a mug, a user is first required to grasp the mug with his/her hand or fingers, lift the mug to the lips, grasp the rim with the lips and then drink from the mug. Thus, the task of drinking from a mug can be grouped into two main tasks – grasping tasks & displacement tasks. These tasks (user functions), determine ergonomic considerations that hold for the mug and for any product that a person will grasp and displace.

2. Ergonomic Constraint representation: For ease of integration into CAD, it is necessary that ergonomic considerations be represented in computable form. In this work, these considerations are represented using algebra and IF THEN rules.
3. Propagation of ergonomic constraints to downstream design activities: To ensure that ergonomics is taken into consideration during the generation of design alternatives and in the determination of the characteristics of the final product, it is necessary that ergonomic constraints be propagated to downstream design activities. In this work, propagation has been achieved by the use of Extensible Markup Language (XML) technology. The methodology just described is illustrated in figure 1.2.

The second step is the testing of the tool to see if it is helpful in reducing design cycle time. To achieve this, the tool is posted on the web and two designers of wheelchair seating system are asked to design a seating system using the current method and then, using the tool. Design cycle time for each method is then compared.

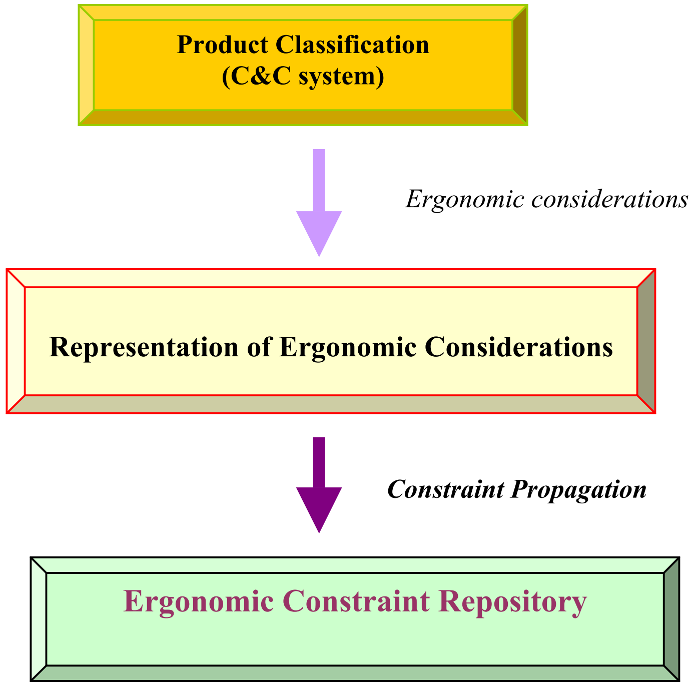

Figure 1.2 Graphical description of methodology

1.4 RESEARCH ORGANIZATION

Chapter 2 presents a review of literature on ergonomics and design while chapter 3 provides the technical background relevant to this work. Chapter 4 describes the methodology developed in this thesis and in chapter 5, the methodology is applied to the design of a seating system. In chapter 6, the hypothesis of this dissertation is tested while Chapter 7 concludes this thesis and discusses other areas of its application and suggestions for future research.

2.0 LITERATURE REVIEW

A number of efforts have been made towards the application of ergonomics to product design. These efforts are discussed in the following sections.

2.1 PHYSICAL ERGONOMIC CONSIDEARTIONS IN PRODUCT DESIGN

Physical ergonomics is guided a set of interrelated principles, which though appear simple and self-evident but are routinely violated in the design of products. Taken as a whole, these tenets represent what to look for in the design of products and finding ways to promote safety and comfort during user-product interaction. The principles of physical ergonomics are:

1. Limit exposure to contact pressure
2. Reduce tissue distortion
3. Reduce moisture in person-product interface
4. Moderate heat build-up in person-product interface
5. Limit exposure to shear forces
6. Reduce application of excessive force
7. Moderate body motions
8. Promote postures of least stress
9. Minimize static load

10. Provide clearance

11. Reduce exposure to vibration and impact forces

2.1.1 Contact Stress, Tissue Distortion, Temperature and Moisture

2.1.1.1 Contact Stress and Tissue Distortion Contact stress results when an area of the body experiences a load, occasionally, repeatedly or continuously. In addition to being uncomfortable and an interference with work performance, contact stress tends to inhibit nerve function and blood flow and if not checked, can cause injury. This rule is therefore imposed when a person makes contact with an object.

Pressure is a function of applied force over a contact surface area. Forces are vectors and are described by both magnitude and direction. Of special interest are normal and shear forces since these play an important role in human-product physical interface. Normal forces act perpendicular to the surface of a body while shear forces act tangential or along the surface. Normal forces, applied to a body results in pressure at the point and if these forces reach a certain magnitude, they can cause tissue breakdown in the affected body region. Shear and frictional forces, occurring at the interface between the human body and a support device, can also cause tissue damage. When normal forces are present in addition to shear forces, a smaller amount of force is required to cause tissue breakdown.[5] Research has also shown that the amount of damage experienced by body tissues is dependent on not just the magnitude of the pressure, but also on its duration.[6] In simple terms, body tissues can withstand higher loads for shorter periods of time.

Tissue tolerance to pressure varies according to the condition of the tissue, the location of pressure, age, weight, hydration, body metabolism, nutrition, neurological state, mobility[7] and activity level,[8] mental status, and medication.[9, 10] As such, the maximal load different individuals or body sites can withstand without damage varies. In fact, research is yet to identify a specific threshold at which loads can be deemed harmful across people or sites of the body. However, manufacturers and practitioners working in the pressure ulcer field use a benchmark load of 32 mm Hg to represent the threshold above which skin damage will occur.[11]

Research has shown that the static comfort (not considering vibration) of a body support surface is dependent on the stiffness of a support surface and a "bottoming" feeling.[12] Research has also determined that contact pressure existing in the person-seat interface, positively correlates with static comfort. As such, the stiffness of a support surface and the "bottoming" effect serve as a measure of the interface pressure a user will experience. The stiffness of a material, usually measured by its Young's modulus of elasticity, E, is a measure of how much a tensile force can change its shape. When a person sits on a flat surface, depending on its material stiffness, the surface will stretch with respect to the tensile force exerted by the weight of the person, and envelop the buttocks. The amount of envelopment determines the amount of contact surface area that is made between the buttocks and the seat surface and correspondingly the amount of contact pressure experienced by the buttocks. A material that is too stiff will not allow a person sink into it while a material that is too soft may "bottom out". In either case, high pressures may be induced on the body issues concerned and as such, it is necessary that the right cushion material be chosen.

Another method for limiting interface pressure is by a pre-contouring a support surface. Pre-contouring a support surface means to shape it so that it closely matches a user's body shape. This permits body envelopment and subsequently, aids in evenly distributing interface pressure.[13]

Another factor that can also affect contact pressure experienced by body tissues is the resilience of the material with which the body makes contact. Resilience merely refers to the ability of a material to absorb energy when deformed elastically and to return it when unloaded. The modulus of resilience measures the resilience of a material and its value simply equals the area under the elastic region of the stress-strain curve.

Tissue distortion has been mentioned as a strong indication of tissue damage.[14, 15, 16] Theoretical and empirical experiments[17, 18] have shown that matching a cushion to the shape of an indenter, which is a rigid device for applying load to a cushion, results in less indenter distortion and interface pressure. This has led to the conclusion that a compliant contoured cushion may be effective in lessening tissue distortion of the buttocks in a seated posture. When soft tissues are subjected to external forces, tissue distortion occurs. When a person sits on a cushion, the buttocks and the cushion deform until an equilibrium interface is reached. Sitting on a hard flat surface causes the buttocks to deform to match the flat shape. However use of a material that yields, enables the buttocks to maintain a less distorted shape.

The contour that occurs in a cushion when a person sits on it is due to five major factors: the shape of the buttocks, the shape of the cushion, biomechanical properties of the buttocks influenced by tissue thickness and stiffness, mechanical properties of foam based on both indentation load deflection (ILD), and density and weight distribution on the cushion.[19] The shape of the buttocks and its tissue properties are difficult to measure and as such, intertrochanteric distance can be used as a measure of the overall size of the pelvis while a person's muscle tone can be used as an index of tissue stiffness. Muscle tone can be categorized as spastic (having too much stiffness), flaccid (little or no stiffness), and normal.

During prolonged sitting, and especially for individuals with sensory and physical disabilities, tilt and recline systems have been determined to assist in pressure relief to the seating areas of the body since these systems enable postural changes. [20] Tilt systems change a person's orientation in space. These systems thus redistributes pressure from one area, such as the buttocks and posterior thighs, to another area such as the posterior trunk while maintaining fixed hip, knee, and ankle angles. Recline systems provide a change in orientation by opening the seat-to-back angle and, in combination with elevating legrests, open the knee angle as well. Recline systems may include armrests that slide back as the seat-to-back angle opens so as to help prevent the arms from slipping.

2.1.1.2 Temperature Higher ambient temperatures have been shown to cause an increase in tissue metabolism and oxygen consumption. Thus, the oxygen requirements of patients, who are at a high risk of developing pressure ulcers and who possess compromised tissue, may be increased. Any increase in temperature in combination with pressure is believed to increase the susceptibility of the tissue to injury either from ischemia or reperfusion when pressure is relieved.

2.1.1.3 Moisture Moisture, along with temperature and the mechanical factors previously mentioned, appears to be another key extrinsic factor in pressure ulcer development. The sources of skin moisture that may predispose the skin to breakdown include perspiration, urine, feces and fistula or wound drainage. Excessive moisture may lead to maceration. It has been theorized that one's risk of skin damage increases fivefold in the presence of moisture. These increases may be due to the slight increase in friction that occurs with light sweating or to the increase in bacterial load resulting when alkaline sources of moisture neutralize the protection provided by the normal acid mantle of the skin.[21]

The ability of moisture to pass through a material is determined by the permeability of that material. Generally, materials of higher permeability rating have a greater ability to allow moisture transfer from a surface of higher moisture concentration to that of a lower moisture concentration.

2.1.1.4 Support Surface Technologies Support surface technologies generally fall into the following five categories: compressive support mediums (elastic foam and viscoelastic foam), fluid-filled, alternating pressure, air-fluidized and low air loss. Surfaces that support individuals in a sitting posture fall into the first three categories while bed support surfaces fall into all categories.

1. Elastic foam support surface: - Elastic foam deforms in proportion to the applied load. Foam is said to have memory due to its ability to return to its nominal shape or thickness when unloaded. The response of support surface made from resilient foam is predominantly elastic. Two basic types of foam is usually used for support surface products – open cell foam and closed cell foam. The minimum density of bed support surface material should be1.3 – 1.6 lbs. Convoluted foam, on the other hand should have a minimum of 4 inches from the bottom to the lowest point of the convolution. Over time and with extended use, foam degrades and loses its stiffness. This usually results in higher interface pressure.

Foam tends to increase skin temperature because foam material and air entrapped air tend to be poor conductors of heat. However, when foam is covered, the rate of heat transfer is more than when the foam is not covered. Use of porous covers on foam products reduce generation of moisture in person-support interface. Nicholson et al has showed that the rate of water transfer was reduced by more than half when foam mattresses were covered by with non-stretch and two-way stretch covers.[22] Movement of the body on a support surface has been shown to increase moisture on the skin surface and therefore affect moisture transfer rates. Stewart has recorded an increase of 10.4% in moisture at the skin surface on foam products after an hour of contact.

2. Viscoelastic foam support surfaces: - Viscoelastic foam is characterized by 100% open-cell foam, which is temperature sensitive, the foam becoming softer at temperatures close to the nominal body temperature. The effect of this softening is that the layer of foam nearest to the body provides improved pressure distribution through envelopment when compared to high resilient foam. The viscoelastic foam behaves like a self-contouring surface because the elastic response diminishes over time even after the foam is compressed. Since viscoelastic foam is temperature and time sensitive, desired effects of these parameters may not be realized when the ambient temperature is too low. More so, properties of viscoelastic foam vary widely and as such, should be chosen based on user needs.

Solid gel support surfaces are also viscoelastic in nature. Gel supports however tend to maintain or decrease skin contact temperature. They tend to have higher heat flux than foam due to the high specific heat of gel material. The heat transfer though, usually decreases after some time and the temperature of the gel might see an increase.[23] With regards to moisture, gel body support cause the relative humidity of the skin surface to increase considerably because of the non-porous nature of the material, usually enclosing the gel.

3. Fluid-Filled support surfaces: - Support surface that are fluid-filled may consist of small or large chambers filled with air, water or other viscous fluid materials such as silicon elastomer, silicon or polyvinyl. In response to movement, fluid usually flows from chamber to chamber,

requiring no additional power. For air filled supports surfaces, care must be taken to maintain the correct levels of inflation in order to limit interface pressure. Under-inflation causes bottoming-out while over-inflation increases interface pressure. When viscous fluid is used, it is important that the distribution of viscous material be monitored since its displacement can result in increases in interface pressure.

Most fluid-filled products allow a high degree of immersion and as such, the body sinks into the surface. The surface conforms to bony prominences, effectively increasing the surface pressure distribution area, thus lowering the interface pressure. Fluid-filled support surfaces generally have very good envelopment characteristics.

The skin temperature of a user is affected by the specific heat of the fluid material contained in the support surface. Water has a high specific heat, while air has a low specific heat. Support surface filled with are therefore good heat conductors while those filled with air are not. Controlling the temperature of the pressurized air in the case of air-filled surfaces can be used to control temperature. The pressurized air can generally be warmed to temperatures in the range of $28^0 – 35^0$ C. With respect to moisture effects during the use of fluid-filled products, use of highly permeable materials allow moisture to be transported away from the body. To limit shear forces, loose fitting but tightly woven materials can be used to cover the support surface.

4. Low Air Loss support surfaces: - Low air loss (LAL) support surfaces are characterized by a series of connected, air-filled cushions or compartments. The devices, which distribute pressure through the principle of immersion, are normally inflated to specific pressures to provide loading resistance based the user’s height, weight and body weight distribution. An air pump, which circulates a continuous flow of air through the support device, also replaces any air that is lost

through the surface's pores. Variations of LAL systems include alternating or pulsating systems. These types of LAL systems have the ability to alternate interface pressure.

In LAL systems, the user's skin is in contact with the cover. The local tissue environment is thus a function of the moisture vapor permeability, air flow, porosity of the cover and support surface materials, and also the thermal insulation of the cover material. The ideal combination of these factors would be a material with a high thermal insulation to prevent excessive loss of body heat, a high moisture vapor permeability to prevent accumulation of excess moisture on the skin, and a moderate airflow to keep the skin from overheating.[24] Flam rated LAL cover materials based on a normalized comparison of these materials and found that the cover the combination of cover made from nylon/high air loss Gore-Tex® laminate material and cushion also made from nylon/high air loss Gore-Tex® laminate material had the highest scores and were most likely to promote a favorable local climate at the skin-cover interface.

Covers for LAL systems are loose fitting to allow envelopment, waterproof, and highly permeable, thus preventing moisture build-up and subsequent skin maceration. Typically, cover materials are made of special nylon or polytetrafluorethylene, which is smooth with a low coefficient of friction, bacteria impermeable, and easy to clean. Similar to the fluid-filled systems, the specific heat of the fluid material (air in this case), affects skin temperature. However, since air is constantly, circulating and evaporating, the skin is kept from overheating. It has been shown that the heat transfer on a LAL mattress is grater than 350 W/m^2.[25]

5. Alternating Pressure support surfaces: - Alternating pressure systems contain air-filled chambers or cylinders arranged lengthwise, interdigitated, or in several other patterns. Air is pumped into the chambers at periodic intervals to inflate and deflate the chambers in opposite

phases thereby changing the location of the contact pressure. Rather than increasing the surface area through immersion and envelopment in order to distribute pressure, alternating pressure devices distribute pressure by shifting the body weight to a different body surface area. This may increase interface pressure at the new body location during the inflation phase. There is however lack of sufficient study of the tissue response to alternating pressure systems in terms of geometry of the surface, material, depth, composition and shape of the supporting structure. Also, in terms of characteristics of the alternating cycle in terms of rise time, hold time, duration of total cycle and pattern of relief, more research is required.

2.1.2 Shear and Friction Forces

Shear and friction forces occurring in the person-product interface can cause skin breakdown. When a person moves, while making physical contact with an object, consideration should be made for shear forces. Body movement against a surface can be voluntary or involuntary. Take the case when a child moves against a playground slide or when a person slides against a support surface in order to transfer to another. This type of sliding movement is voluntary. However, when a wheelchair user experiences perturbations during ambulation causing his/her body to undergo slight displacements against the seating support surface, such motions are involuntary and will also generate shear forces on the body of the user. During sitting, shear force can be minimized by inclining the thigh-support slightly above the horizontal to match the angle of backrest-recline. If the thigh support is inclined in this way and the seat surface combines a pelvic recess, the body is cradled and all tendencies to slide are virtually eliminated (figure 2-1). Also since some friction is necessary to prevent a person from simply sliding off the support surface in situations such as sitting in bed or in a wheelchair, to reduce tissue damage, friction should only be applied to low risk areas of the support surface and kept to the barest minimum near high-risk areas surrounding bony prominences.

Material layers interposed between a person and an object play a significant role in the amount of shear force generated in the skin-object interface. Therefore, the right choice of material may minimize friction in the person-object interface, which would be valuable in minimizing tissue damage due to shear. The ideal material should be thin, flexible and stretchable.

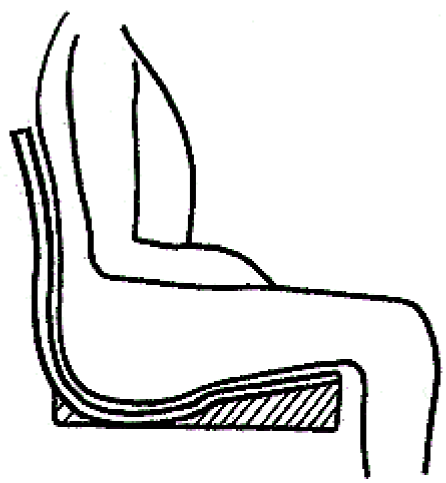

Figure 2-1Upward inclined seat surface combined with pelvic recess to reduce shear force

2.1.3 Static Load

Holding the same position for a period of time is known as static load and can cause pain and fatigue. Work activities often necessitate prolonged sitting and standing postures.[26, 27] Abnormalities of the spinal column have come to mean prolonged sitting while use of hand tools often keeps the hand in a grasping position for long periods.[28] Consideration for static loading should thus be made when a person will maintain a static posture for prolonged periods.

When the hand will grasp for long periods, it is necessary to use straps to fixture the object to be grasped to the hand or fingers, so as to reduce static load. For products utilizing an input device, provision of an multiple input devices will help reduce static load since users can alternate between the multiple devices. A good example is to provide a touch pad as well as a mouse for a laptop computer. Another is to provide cruise control in a vehicle.

Also, use of armrests in sitting and standing tasks help reduce static load to the shoulders will latches can be used to temporarily keep a lid or door open or hold an object down. Trigger locks on power tools and self-closing door cylinders serve as good examples of use of latches. For products having components to be assembled, use of guides and funnels can help quicker assembly time and so reduce the amount of time muscles are tensed while grasping. During continuous sitting, a means should be provided to change body orientation and reduce static load on muscles.

2.1.4 Moderate Excessive Body Motions

The number of motions required to perform a task can have a profound impact on the wear and tear on the body as well as on productivity. Excess body motions can create injuries to delicate body tissues and as such should be reduced. Some products require body motions in order to be operated such as those needing to be displaced or those requiring body gestures to generate a response. For these groups of products, considerations ought to be made for the amount of movements an operator requires to operate them in accomplishing tasks.

2.1.5 Forceful Body Exertions

When the human body is caused to exert undue force, the muscles can be overloaded, become fatigued and may even develop an injury. A product that requires excessive force for its operation in order for a person to accomplish a task may actually interfere with the ability for one to achieve one's task objective. Duration is an important consideration in dealing with force. A force that is sustained for a few minutes has a different implication from that which is sustained for a few seconds.

Forceful exertions will occur when the force required to displace objects is more than that which individuals can safely exert. An individual's ability to manually displace a load is based on such variables as frequency of load handling, direction in which the load will be moved, (figure 2-2) location of load relative to the person, (figure 2-3), whether the load requires static or dynamic body movements for displacing it, and environmental factors such as temperature, altitude, and humidity. Intrinsic factors of the individual, which determine the amount of force or torque he/she can exert to displace an object, are the person's muscular strength, training, experience, skills, and body posture.[29, 30, 31, 32]

Displacement is the distance, translational or rotational, that a point on the surface of an object travels from its initial position to its post-analysis position. The total displacement is represented by components in each of the three translational directions and the three rotational directions.

There are two major sets of recommendations applicable in the workplace for determining permissible loads for handling. These are those of NIOSH and those of Ciriello et al.[33, 34] The first set of NIOSH guidelines, limited to lifting and lowering were provided in 1981. These guidelines established two different threshold curves, the lower threshold curve, called the

Action Limit (AL) and the upper threshold curve called the Maximum Permissible Load (MPL). If a weight to be lifted was above the AL value, it was necessary to apply engineering or managerial controls to bring the load down to an acceptable level. If a load was three times larger than the AL value, the lifting task was unacceptable. In 1991, NIOSH revised its guidelines such that the new guidelines simply provided a Recommended Weight Limit (RWL). RWL represents the maximal weight of a load that may be lifted or lowered under the best possible conditions by about 90% of American industrial workers, male or female, physically fit, and accustomed to physical labor. Using the RWL value, the Lifting Index (LI) is computed and for LI values of one or less, no action is required. However, if the LI value is greater than one, ergonomic intervention becomes necessary in order to prevent possible human injury.

The guidelines published by Ciriello et al provide recommendations for loads and forces that are acceptable to males and females for continuous manual material-handling tasks. Unlike those of NIOSH, these recommendations have a wider application, and pertain to pushing, pulling and carrying in addition to lifting and lowering.

For handheld products, such as cell phones, hair dryers, pocket calculators, and tennis racquets, a number of authors have provided guidelines for designing them for human safety and comfort.[35, 36, 37] Products that are carried comfortably for at least 10 minutes without resting are termed portable products while those that are required to be carried for short distances only, (up to 125 meters), with rest allowed whenever necessary, are termed transportable products. Portable products include personal radios, walkman and cell phones while transportable products include small television sets and VCRs.

Many products may not be frequently held nor carried. Such products include refrigerators, photocopiers, and printers. Also included in this category are products that are normally set up or installed by a user in the home environment such as the microwave oven. For this group of products, the guidelines provided by Rosenberg[38] and Snook and Cirello[39] apply.

Attaching handles to loads that are manually handled have been determined to reduce loading on the spine[40, 41, 42] and increase the time users can carry the load.[43]

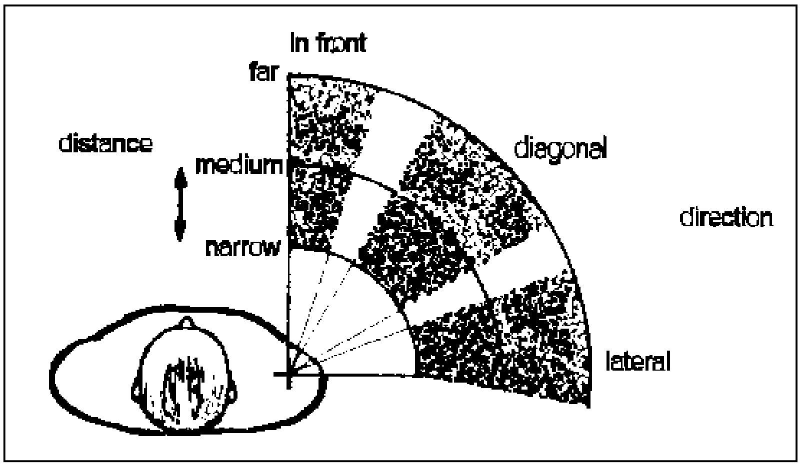

Figure 2-2 Directions in which forces are exerted

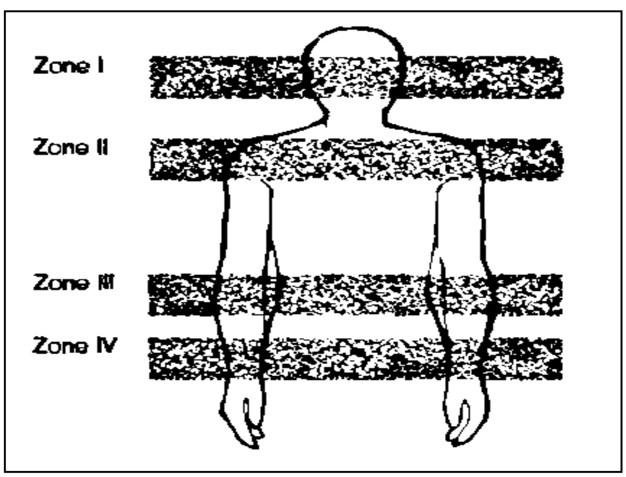

Figure 2-3 Locations of forces exerted

2.1.6 Body Positions of Least Stress

Long reaches place the body in awkward postures the latter being a risk factor for the occurrence of musculoskeletal disorders (MSDs). Thus, if the position of a product or its parts is constrained in space and a person needs to access any part of the product while in a constrained posture, this rule will apply. Reach contours have been determined for males and females in the U.S. Air Force.[44] Goldsmith have also provide reach measurements for adults who use wheelchairs and also for elderly people.[45]

The neutral posture is the optimal position of each joint that provides the most strength, the most control over movements, and the least physical stress on a joint and surrounding tissues. In general, this position is close to the midpoint of the full range of motions where the muscles surrounding a joint are equally balanced and relaxed. However, the posture of the arms and the knees are exceptions to this rule. Since gravity affects the arms, the latter tend to hang down close to the body while the knees tend to function well near their extreme extended position.

A point worth noting is that the above is true for individuals without physical disabilities of the joints. For individuals with abnormal joint functioning such as those suffering from arthritis, spinal cord injuries, etc, the optimal positioning of their joints will be individual specific and will be the position that produces the minimal joint discomfort.

For populations without disabilities of the joints, the neutral posture is supported:

1. For the finger joints: - when the fingers are gently curved, in their natural resting position, not spread apart, not fully straightened out (extended) nor tightly curled (flexed).

2. For the wrist joint: - when the wrist is inline with the forearm, neither bent up (extension) nor bent down (flexion). Further, the neutral posture is supported when the wrist is neither bent towards the thumb (radial deviation) nor towards the little finger (ulnar deviation).
3. For the elbow joint: - when the forearm rests with the thumb up and is neither rotated to make the palm face down (pronation) nor up (supination), and the angle between the forearm and the upper arm is about 90^0
4. For the shoulder joints: - When the upper arm hangs straight down, and is not pulled across in front of the body (adduction) not elevated to the side (abduction), not raised to the front of the body (flexion) nor raised towards the back (extension). To further promote the neutral posture, the shoulders should not be hunched up, not pulled down, and not pulled forward or back.
5. For the neck joint: - When the head is balance on the spinal column and is not tilted forward, back or to either side. Also, the neutral posture is promoted when the head is neither rotated to the left or right.
6. The back: - When the spine naturally assumes an S-shaped curve, with the upper spine (thoracic region) bent gently out in *kyphosis*, the lower spine (lumbar region) bent gently in, in *lordosis*, the spine not rotated (or twisted) to the left or right, and not bent to the left or right.
7. The lower body: - In the neutral position, the lower body assumes a fetal position with hip and knee joints somewhat bent. This means that both seated and standing postures involve deviations from neutral posture.

2.1.7 Clearance

Providing adequate clearance for the body is important for several reasons. Adequate clearance for the body prevents collisions with objects. Also, while a user ambulates while in physical contact with a product, clearance need to be provided to reduce collisions between the product, the person and other objects in the environment, since these collisions cause physical stress. Different authors have provided guidelines for the design of access openings. Some of these are the guidelines by U.S. military[46] and Woodson.[47] For products which are gripped during ambulation such as briefcases, Cushman and Rosenberg have provided guidelines for design them for adequate clearance.[48]

2.1.8 Vibration

Vibration is the oscillatory motion of bodies which have mass and are elastic. These include engineering machines and the human body. Two classes of vibration are distinguished – free vibration and forced vibration. Free vibration exists when a body oscillates under the action of internal forces only, that is, when the system vibrates at one or more of its internal frequencies. Forced vibration on the other hand, is caused by external forces. If the frequency of excitation coincides with the natural frequency of the system, resonance occurs which causes an amplification of motion. What results, are large oscillations within the system, which can create potentially harmful stresses. This is the reason forced vibration to the human body must be minimized and possibly eliminated.

The human body reacts in a complex way to vibrational stimulus and this reaction is dependent on the frequency, amplitude and direction of the vibration as well as the duration of exposure to the vibration. When a person's entire body reacts to vibration, it is referred to as whole-body vibration while segmental vibration occurs when only certain bodies segments experience vibration.

The coordinate system for describing the direction of whole-body vibration of the human differs from that used in other applications. In vibration research, the x-axis is in the forward direction in reference to the vibrating body, the y-axis points to the left while the z-axis points upwards. For hand-arm vibration, that is segmental vibration, two coordinate systems are proposed – a basicentric system centered on the surface of the handle of the vibrating tool and an anatomical biodynamic system centered on the third metacarpal bone of the hand. In describing the magnitude of vibration, displacement, velocity or acceleration over time, is utilized.

Several attempts have been made to formulate guidelines for exposure of humans to vibration resulting from human-product interaction. Some of these are ISO 2631, for whole body vibration and ISO 5349, for hand-transmitted vibration.[49]

2.2 APPLICATION OF ERGONOMIC DATA TO PRODUCT DESIGN

In implementing the principles of ergonomics towards achieving good design, use of anthropometric and strength data is necessary. Such data must not only be appropriate to the design at hand but must also be descriptive of the target user population. When ergonomic data is applied to product design, data is either taken from the specific population for whom the design is being made or in the case of a customized design, taken directly from the individual.

Currently, several anthropometric data sources exist in literature. One is that by Webb Associates which provides over 300 different human sizes and form variables for Americans, Europeans, and Asian populations.[50] These authors have also derived specific regression equations for the lengths of bones in extremities as a function of stature.[51] Their equations indicate that the standard error is approximately 1.0 cm when stature is used as the basis for the bone-length estimates. The error increases slightly though when bone lengths are converted to link lengths since it is difficult to determine the precise center of rotation for a link. Also, for link lengths, data have been derived on living subjects with reference to stature. Statistical regressions of link lengths on stature have also been performed and from these regressions, values are given as proportions of stature and as percentiles of the population. An example is the work of Drillis and Contini, presented by Roebuck et al (figure 2.4).[52] Dempster[53] has provided link boundaries and locations of center of mass as a percentage of link lengths (figure 2.5). For populations with disabilities a large body of anthropometric data has been complied on more than 11,000 persons of every age and a wide variety of disabilities. However, most of these studies are on specialized populations, many of them foreign and the definition of dimensions and measurement techniques vary from study to study and, in many cases, the studies apply to very small sample sizes. An example is the work of Goswami et al[54] who have presented anthropometric measurements of disabled Indian men whose disabilities are as a result of poliomyelitis.

Recently, a computer-based anthropometric data source, known as PEOPLESIZE[55], has been developed by Open Ergonomics Ltd. PEOPLESIZE is a software package, which provides information on body measurements through the use of a visual interface. To obtain body measurements using the software, the nationality, age group and percentile value of the target population is first specified. Next, the body part for which dimensions are required, is visually selected, the software then makes adjustments for clothing and sitting slump and subsequently provides the necessary anthropometric data on an output dialog. The software also has the capability of exporting the data in Microsoft Word format, Text format, or Spreadsheet format. PEOPLESIZE provides over two hundred and eighty body dimensions covering adults in the United Kingdom, United States, China, Holland, France, Germany, Italy and Japan. It also provides data for infants and children in the United Kingdom and United States, from birth to age seventeen years.

Most body-segment strength data are available for static exertions and provide reasonable guidance for slow motions. Of the scanty information available regarding dynamic strength exertions, much is limited to constant-velocity cases. Some strength data available in literature are those by the U.S. Department of defense.[56]

A point worth noting is that ergonomic data, computerized or not, simply provides the bounds for ergonomic constraints from the point of view of the human. For example, ergonomic data provides information on the body dimensions and strength capabilities of product users. However, such data are ergonomic constraints from the human perspective and not the product perspective. More so, the data do not inform the designer of ergonomic rules (constraints) that apply to a design context. A designer is required to determine these rules and the necessary anthropometric data that apply to the design context, and then reformat the data to determine the constraints that should guide the product design. This process is circuitous and thus, time-consuming. This work specifies applicable ergonomic constraints as design specifications and then utilizes ergonomic data in the determination of limits for the constraints.

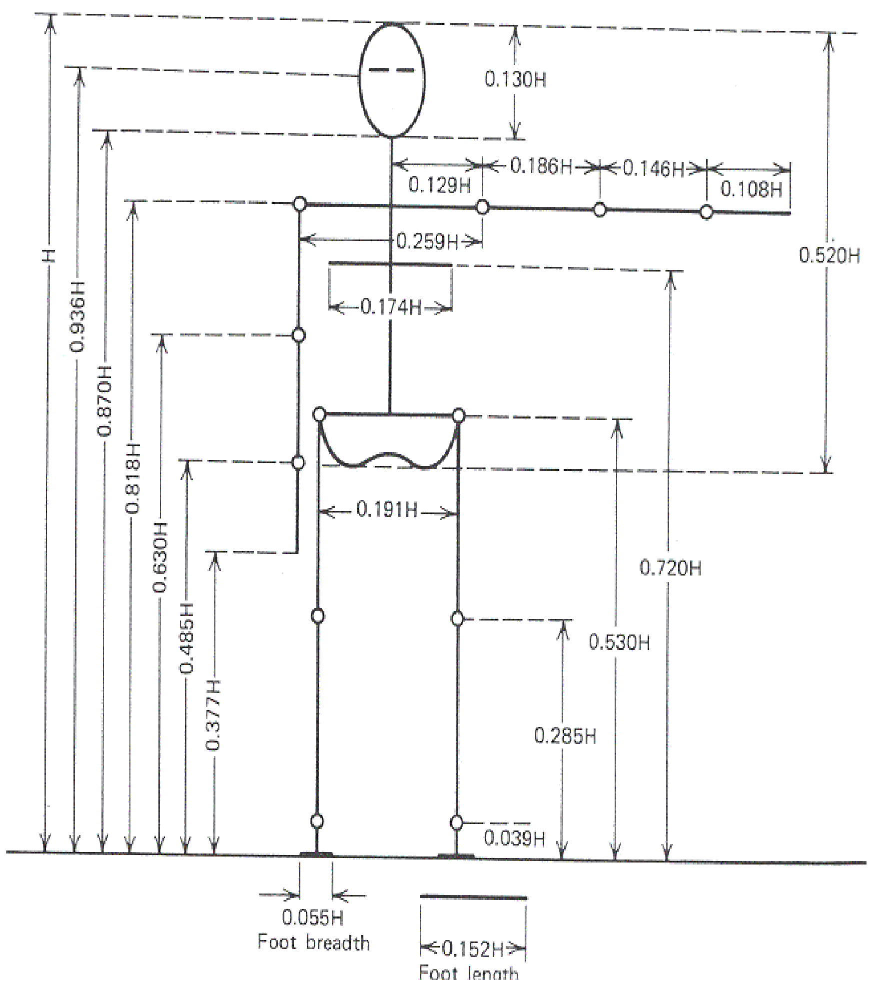

Figure 2.4 Segment lengths expressed as ratio of stature. *Courtesy of Roebuck et al*[57]

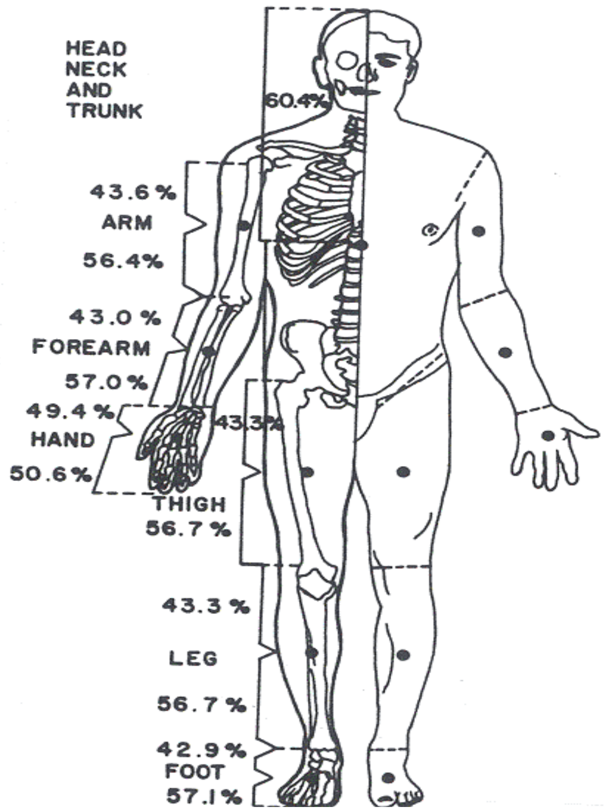

Figure 2.5 Link boundaries and locations of center of mass as a percentage of link lengths.
Courtesy of Dempster[58]

2.3 APPLICATION OF DESIGN RECOMMENDATIONS TO PRODUCT DESIGN

Design recommendations in advance, take into consideration the context of product use and the anthropometry of the target population and then provide a designer product design specifications based on the principles of ergonomics. A number of authors have provided design recommendations for use in product design. Some of these works include those by Dreyfuss,[59] Diffrient et al[60, 61], Panero and Zelnik [62,] Woodson[63], Tilley[64] and the American National Standards for wheelchairs and scooters.[65]

Design recommendations available in literature provide specifications for design on a product-by-product basis. In order to determine product specifications that satisfy ergonomics, a designer is therefore required to consult literature. Considering the thousands of everyday products, not even taking into account the components that make up these products, this process of obtaining product specifications that satisfy ergonomics is apparently inefficient as it can be time consuming. Recently, a group has developed a software known as Ergonomics Knowledge and Intelligent Design System (EKIDES),[66] which assists designers of technical systems, equipment, products and workplaces in meeting ergonomic requirements for system components and their interactions, during the planning, development and subsequent design and blueprint processes. EKIDES is a design tool in the form of an electronic reference system and an evaluation tool for work places and products. Its capability in product design, however, is limited to providing a checklist for ergonomic issues in the design of cars, buses/coaches, trucks/heavy lorries and machinery for construction sites.

Another design tool, Automotive Designers Ergonomics Clarification Toolset (ADECT)[67] provides a structure for systematic investigation and recording of ergonomic issues in the early stages of automotive design. This tool is based on Human Factors Tools for Designers of Information Technology (HUFIT),[68] and goes beyond the checklist approach. ADECT however is limited to automotive design and more so, some designers perceive the use of ADECT as onerous.[69]

Norris et al[70] have provided a tool for evaluating a product for ergonomic issues. Their tool is targeted towards product designers and production teams, working without any ergonomic support, and who would be unlikely to independently access information on ergonomic methods and techniques. Their tool consists of 4 parts (figure 2.6) – identification of all possible users; identification of all possible hazards; setting of performance criteria and test variables; and selection of testing materials. In identifying all possible hazards, their proposed method for incorporating ergonomic considerations is by use of experts or product users. Essentially, these individuals are required to mentally perform design appraisals to determine potential hazards. The work of these authors does not address the manner in which the result of the evaluation process will be represented and presented to the designer in a CAD environment. Their method of incorporating ergonomics into product design is highly manual, can be tedious and does not facilitate ease of integration of ergonomics into CAD.

Some s*tate of the art* tools for ergonomic design analysis are SAFEWORK Pro[71] and EDS JACK.[72] These tools generally provide a designer the capability to analyze a detailed design for ergonomic violations with respect to posture, fit, clearance and reach. However when a design has not been guided from the onset by ergonomic design principles, application of these tools in detailed design analysis would likely identify major ergonomic violations, correspondingly requiring numerous and costly design changes. One tool called System for Aiding Man-Machine Interaction Evaluation (SAMMIE)[73] has been applied in the conceptual design of a racing car. Its application to conceptual design though, requires a great amount of manual input in determining the fit and reach requirements of the driver.[74] Another tool that has been developed is the Ergonomics Design Knowledge Based Expert System (EDKBES)[75], which simply integrates an expert system into SAMMIE. EDKBES however is limited to the design of vehicle interiors.

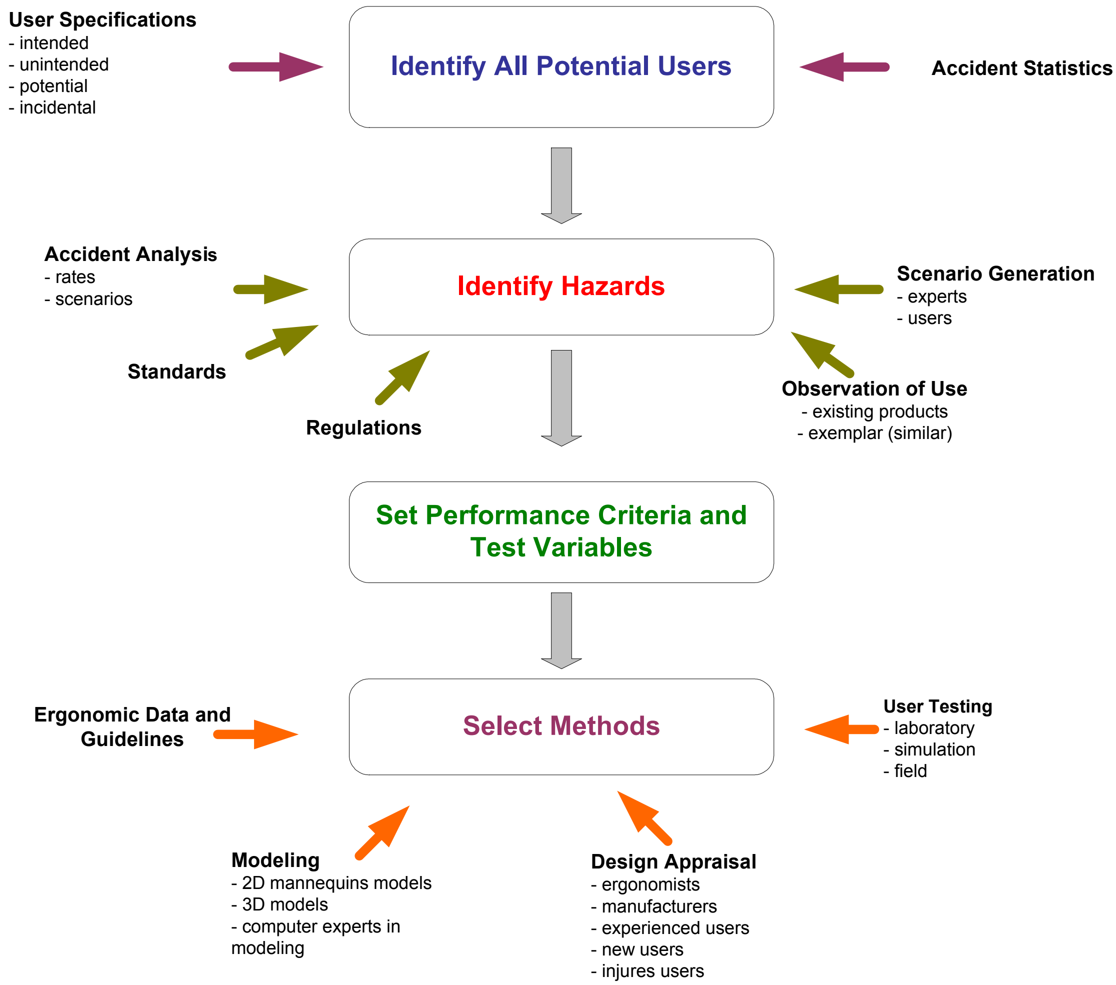

Figure 2.6 A framework for the product evaluation process. *Copyright: Norris B. and Wilson J.*[76]

2.4 PRODUCT CATEGORIZATION FOR MAKING ERGONOMICS CONSIDERATIONS

A few product categories exist for which guidelines have been provided for making ergonomic considerations. One of these is the category for hand held products such as hair dryers, telephone sets, tennis racquets, manual and power tools.[77] Some ergonomic guidelines governing products in this category are avoidance of sharp edges on surfaces to be gripped and fitting handle diameter to force requirements. Another product category is that for portable and transportable products.[78] Design guidelines for this category constrain weight, size and handle design for products belonging in its class. Other product categories are those for controllers[79] and for equipment used in MMH, such as forklifts.[80]

However, there are many products that are not categorized and for which existing categorizations do not fully determine relevant ergonomic principles, which should govern them. Examples include the mouth stick, a product used by the mouth; and beds, which are products on which the body rests. For some of these products, design standards are provided mostly as literary material and on a product-by-product basis. For a product such as the “bubbles-making” toy, and many other products, no design standards exist. Since most standards exist on a product-by-product basis, it is infeasible to efficiently capture this information and implement it in a computer-based tool to guide designers in meeting safety and comfort requirements. To overcome this, discrete everyday products have been classified in this thesis and ergonomic principles constraining each product class, stipulated. This classification can be generalized to different discrete products and due to its concise structure, lends itself to computer implementation to provide guidance in CAPD.

2.5 ERGONOMIC SOFTWARE TOOLS

In the following tables, some existing ergonomic software tools are listed for product design and manual material handling (MMH).

Table 2.1a: Product Design Software Tools

Name	Maker	Capabilities
SafeWork Pro	Nexgen Ergonomics Inc.	Investigates Human Product Interaction w.r.t postural analysis, collision detection, vision, etc. Incorporates ACIS Universal File Translator.
Jack	EDS	Evaluates Fit, Reach and Posture in product design
SAMMIE	SAMMIE CAD Ltd	Fit, reach, postural and visual analysis

Table 2.1b: Manual Material Handling/Biomechanical Analysis

Name	Maker	Capabilities
3D Static Strength and Prediction Program (3DSSP)	University of Michigan: Center for Ergonomics	Used for analyzing MMH tasks, predicting static strength requirements for such tasks as lifts, presses, pushes and pulls. Performs posture and biomechanical analysis. Predicts the percentile of males/females that can perform a certain job.
ErgoMaster	Nexgen Ergonomics Inc.	Integrates photo images and videos of tasks with 3DSSP, NIOSH lifting index and Rapid Upper Limb Assessment (RULA).

(Table 2.1b cont'd)

ErgoEase	Ease Inc	Analyses operator methods for ergonomic impact. Covers strength, force, fatigue, posture, recovery, workstation and operator recovery discomfort analysis.
MAC Software	Daniel McCrobie	Allows the calculation of lifting limits for individuals based on a variety of situations. Tool is based on NIOSH lifting guidelines.

2.6 CONCLUSION

Existing tools for integrating ergonomic principles into a CAD environment, are applicable to the evaluation stage of CAD and do not aid conceptual design at which stage most cost bearing decision need to be made.

Current means of applying ergonomic data to product design is circuitous since the data needs to be reprocessed as design specifications before use. Most design specifications data exist as literature materials and are specified on a product-by-product basis. A designer is thus required to consult literature in order to determine relevant ergonomic design specifications pertaining to a product's design. This can be a lengthy process and thus wasteful in terms of time and money. Further, only a handful of product categories exist for making considerations for ergonomics. Since standards exist on a product-by-product basis for many everyday products, designers cannot efficiently determine information they require. Due to the structure of the standards it becomes impractical to concisely capture standards for all products and implement the information into a computer-based tool. Notably, available computer-based tools such as EKIDES, only address a handful of products.

State of the art CAD analysis tools for ergonomics, such as SAFEWORK Pro are applied to detailed design. Any major ergonomic violations they determine would thus require costly design alterations. This can be expensive in terms of time and money. More so, these tools are limited to ergonomic analysis for fit, reach, clearance and posture. This is not exhaustive, as the tools do not provide design analysis for conformance to all ergonomic rules. For example, none of these tools analyzes a design for conformance to the rule of minimization of static loads on the body.

Based on the premise, a more effective and efficient means for integrating ergonomic considerations into the conceptual stage of computer-aided product design greatly required. This work provides a comprehensive and concise categorization of discrete products for making considerations for ergonomics and implements classification in a computing environment. The categorization makes for ease of determination of all ergonomic principles relevant to a product's design in an efficient manner as opposed to the current method of determining ergonomic principles on a product-by-product basis. Also, the product categorization provided, has the advantage of being applied to not only to existing designs but also to new designs. The rules prescribed by the taxonomy are mathematically represented so that they are easily integrated into a CAD environment. Finally a means is provided for presenting ergonomic constraints to detailed design activities.

3.0 BACKGROUND INFORMATION

3.1 INTRODUCTION

Ergonomics is an interdisciplinary field of study that seeks to design systems in which people play a significant role such that the interrelationship between the human and the system is optimized. A system could be a simple hand tool, a complex product such as an automobile, or an organization's workplace including the associated tasks that are performed.

K. F. H. Murell first derived the word ergonomics in 1949 from the Greek word *ergon* meaning work and effort, and *nomos*, meaning law or usage. Today, ergonomics is called different names, for instance, Human Factors engineering, Human Engineering, and Industrial Psychology. Various authors have provided different definitions of ergonomics. Kroemer et al[81] define ergonomics as the study of human characteristics for the appropriate design of the living and work environment. Their philosophy is that the fundamental aim of ergonomics is that all human-made tools, devices, equipment, machines, and environments should advance, directly or indirectly, the safety, well-being, and performance of human beings. Chaffin et al[82] define ergonomics as a systematic and rational means of fitting the work to the person and has the primary goal of improving worker performance and safety through the study and development of general principles that govern the interaction of people and their working environment.

Ergonomics has a physical aspect and a cognitive aspect. Physical ergonomics is concerned with fitting the physical aspect of the human, that is, body size, body shape and strength capabilities, to design while cognitive ergonomics focuses on providing a fit between a person's mental capabilities and a design at hand. In the United States, Physical ergonomics is simply referred to as ergonomics while cognitive ergonomics is called human factors. This dissertation is concerned with physical ergonomics, and the latter will simply be called ergonomics and is defined as the body of knowledge concerned with the study of human capabilities and limitations to be used in the design of systems, which may be products, tasks, and environments, to ensure that biomechanical stresses to the user are minimized and that safety and human performance are optimized.

There are three basic human factors that should be accommodated in design: one is that people are different in shape and size, two, that people have limitations physically and mentally, and three that people have predictable reactions to events based on their life experiences. Ergonomics, applied to product design is a technology for creating products that is agreeable to the physical characteristics of product users and has the objective of ensuring that these end-users interact with products safely so that their work output is maximized. In ergonomics, design begins with an understanding of the user's role in the overall product/system performance and products/systems exist to serve their users, whether they are consumers, system operators, production workers, or maintenance crews.

Section 3.2 outlines the various organizations associated with the discipline of ergonomics while Section 3.3 discusses the sciences providing input to the field. Section 3.4 provides background information on musculoskeletal disorders and ergonomic risk factors, section 3.5 outlines ergonomics in relation to product design, sections 3.6 and 3.7 present information on algebraic constraint representation and the extensible markup language, respectively.

3.2 ORGANIZATIONS ASSOCIATED WITH ERGONOMICS

There are several bodies that provide guidelines for designing for human use. These bodies are:

OSHA – Occupational Safety and Health Commission

NIOSH – National Institute of Occupational Safety and Health

HFES – Human Factors and Ergonomics Society

IIE – Institute of Industrial Engineers

ASSE – American Society of Safety Engineers

AIHA – American Industrial Hygiene Association

ES – Ergonomics Society

RESNA – Rehabilitation Engineering & Assistive Technology Society of North America

BMES – Biomedical Engineering Society

EMBS – Engineering in Medicine and Biology Society

ILO – International Labor Organization

IEA – International Ergonomics Association

ISO - International Organization for Standardization

3.3 SCIENCES PROVIDING INPUT TO ERGONOMICS

Several classical sciences provide fundamental knowledge about human beings. The anthropological basis of such knowledge consists of anatomy, which describes the build of the human body; orthopedics, concerned with the skeletal system; physiology, dealing with the functions and activities of the living body including the physical and chemical processes involved; medicine, which is concerned with illnesses and their prevention and healing; psychology, the science of mind and behavior; sociology, concerned with the development, structure, iteration and behavior of individuals and groups; and Engineering, which is concerned with the application of scientific principles and techniques to design. Other classical sciences, which also supply knowledge, approaches, and techniques to ergonomics, are physics, chemistry, mathematics, and statistics.

3.3.1 Anthropology

Anthropology is known as the study of mankind with particular emphasis on human culture and human development.[83] Physical anthropology, a subgroup of anthropology, is concerned with studying and measuring the body, particularly the bones, and then comparing these physical measurements, among different groups of people in different geographical locations. In the middle of the nineteenth century, the Belgian statistician Adolphe Quetelet first applied statistics to anthropological data.[84] This gave birth to modern anthropometry, the scientific measurement of the human body.

3.3.2 Anthropometry

Anthropometry is an empirical science that attempts to define reliable physical measures of a person's size, mass, form and inertial properties for anthropological comparison. Engineering anthropometry stresses the application of these measurements in developing and evaluating engineering designs and mock-ups to assure that reach, clearance, and visibility requirements are met in various strata of the population. Anthropometric measurements are typically done with a person standing, sitting, laying face up (supine posture) or down. For functional anthropometry, that is anthropometry determined from postures assumed during work, measurements are dependent on stated or implied assumptions. An example is that of functional reach dimensions for individuals seated in a wheelchair while performing activities of daily living (ADL).

There are different methods for measuring anthropometric parameters. For determining center of mass, the *suspension technique*[85] for cadavers and the force platform methods[86,87] for living subjects can be used. For moments of inertia measurements, the *pendulum method*[88, 89] can be used for cadavers and living individuals, the *quick release method* and the *incremental submersion method* may also be used.

3.3.2.1 Application of Anthropometry Data to Design There are five basic steps required for the correct use of anthropometric data.90 These are:

1. Definition of the design problem
2. Determination of the combination of body dimensions relevant to fitting the design to its target users. This is known as case selection.[91]
3. Definition of the anticipated user population.
4. Acquisition of appropriate anthropometric data on the relevant body measurements (or multivariate summary statistics) for a specific sample of people representing the body size variations of the user population. The clothing type to be worn by the users of the design need also be taken into account.
5. Determination of the clothing type to be worn while product is being utilized and then making allowance for clothing

3.3.3 Joint Motion

Joint motion also referred to as joint mobility or joint flexibility, is generally defined according to the amount of motion produced at the joint. This measure is normally acceptable for primary simple joint rotation found when a person flexes or extends the elbow or knee. For joints at the knees or shoulders, motion is referenced to a particular plane – Sagittal, Coronal (frontal) or Transverse planes. For individuals without physical disabilities, a set of definitions have been developed for all major joints which assumes that motion is measured with a person in the standard anatomical position. This is illustrated in figure 3.1 below. The position requires a person to stand erect, face forward, and hold the arms down at the side with palms facing forward (i.e thumbs point away from the body).

3.3.3.1 The Neutral Posture The neutral posture has been defined as position of least stress or highest strength for each joint[92] or simply the midpoint of range of motion of the human muscles, tendons, ligaments, and joints, exceptions being the joints of the arms and knees. OSHA defines the neutral posture as the position of a body joint, which requires the least amount of muscle activity to maintain. For example, the neutral posture is promoted when the wrist is in a handshake position, when the elbow is near the waist, and when a person is standing up straight such that the back assumes its natural S-curve.[93]Another definition of the neutral posture is that it is the posture of an astronaut in a weightless environment. When a body is in space and there is no force acting on it, the body simply assumes the neutral posture position.

The neutral position is often intuitively assumed to mean straight, such as when hand and forearm are aligned. For most joints though, the neutral position remains undefined. There are however, desirable body postures recommended when a person works or interacts with a product. Also, it must be noted that when a body is in a sitting or standing posture, it is not in the neutral body position.

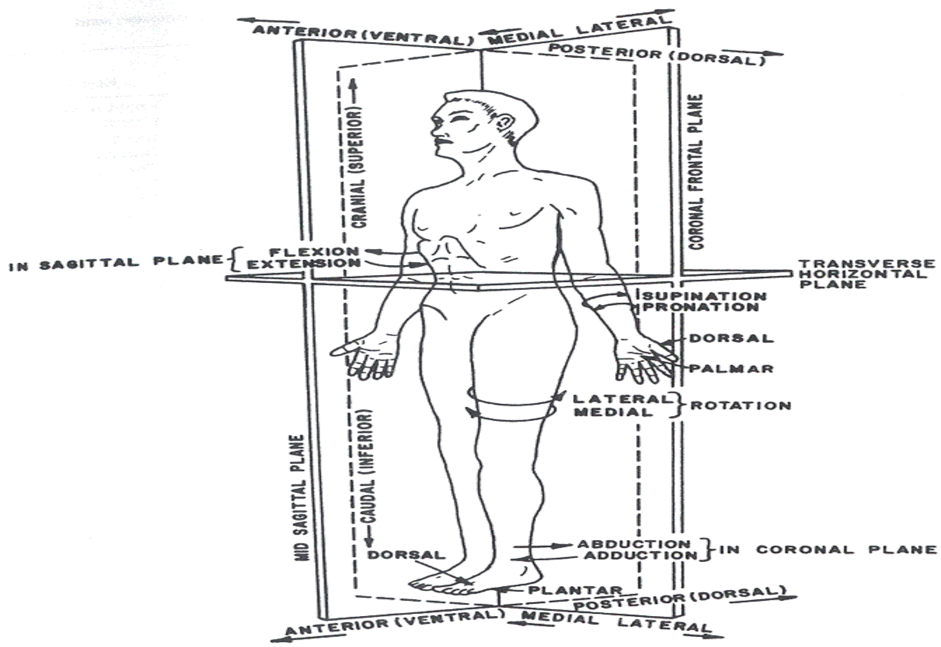

Figure 3.1 Standard anatomical position showing classical terminology for major movements

3.3.4 Biomechanics

Frankel and Nordin[94] have defined biomechanics as the use of physics and engineering principles to describe motion undergone by the various body segments and the forces acting on these body parts during normal activities. The human body is often considered in mechanical terms and is modeled as consisting of long links, which are connected to each other at articulations (joints) having various degrees of freedom, powered by muscles that bridge the articulations and associated with volumes and mass properties. To explain the effects of external impulses applied to the human body, Isaac Newton's (1642-1727) physical laws are then used. The components of the biomechanical models of the human body are described with the following analogies:

- Bones - lever arms, central axes, structural members

- Articulations – joints and bearing surfaces
- Tendons – cables transmitting muscle forces
- Tendon Sheaths – pulleys and sliding surfaces
- Flesh – volumes and masses
- Body Contours – surface of geometric bodies
- Nerves – control and feedback circuits
- Muscles – motors, dampers, or locks
- Organs – generators or consumers of energy

3.3.5 Human Physiological System

Human physiological system consists of three major parts – respiratory, circulatory, and metabolic. The respiratory system provides oxygen for energy metabolism and dissipates metabolic by-products. The circulatory system carries oxygen, derivatives of carbohydrates and fats to the cells that require them while the metabolic system support the chemical processes in the body, particularly those that yield energy.

The ability to perform physical work is different from one individual to another. This ability depends on gender, age, body size, the environment concerned and motivation factors. Figure 3.2 illustrates how these determining factors affect an individual's capability for physical work.

There are different measures of physical work capability. Some of these are Oxygen (O_2) uptake, respiratory quotient (RQ), calorific value of O_2 uptake and a count of the heart rate. Standardized tests can also be conducted for O_2 consumption using bicycle ergonometers, treadmills, or steps. Techniques for measuring work capability include indirect calorimetry for O_2 uptake, subjective methods for perceived effort, for example using BORG's scales for rating of perceived exertions (RPE) and CR-10.

Knowledge of the energy requirements of a task allows one to judge the difficulty level of the task. With light and medium work, metabolic and other physiological functions can attain a steady state throughout the work period, provided that the individual concerned is trained and capable. With very heavy work however, this is not usually the case. Because oxygen deficit and lactic acid concentration increases throughout the duration of very heavy work, it is necessary that a person involved in such a task rest intermittently. To arrange for a suitable match between a task's energy demand and a person's energy capability, a designer will need to adjust the task to be performed to the capabilities of the human concerned.

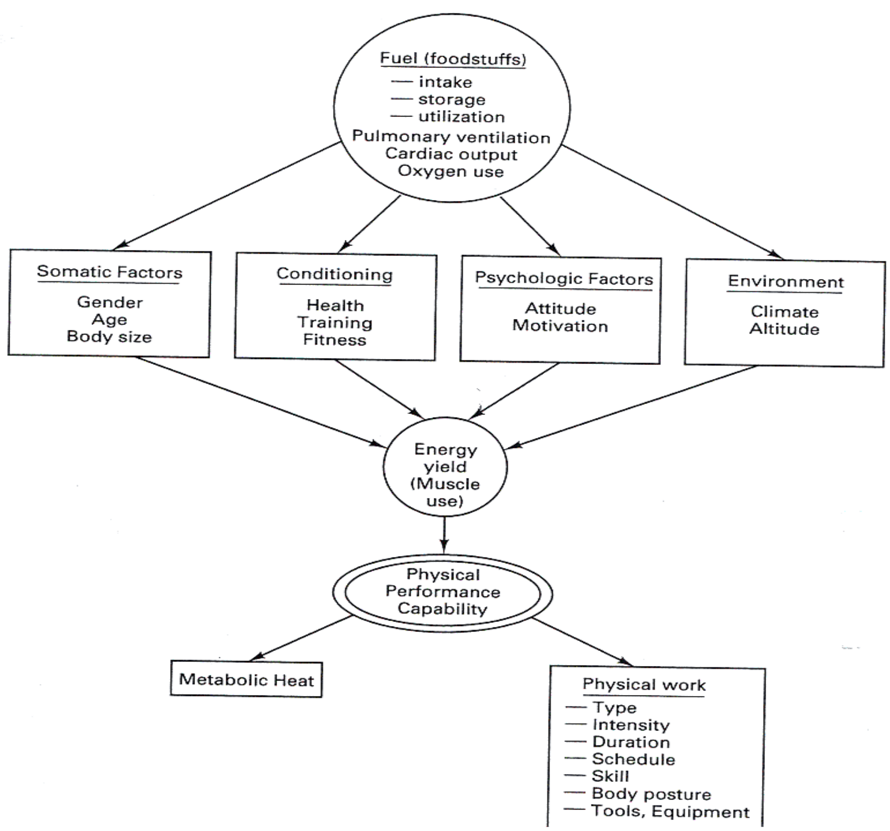

Figure 3.2 Factors determining an individual's physical work capability

3.4 MUSCULOSKELETAL DISORDERS

Musculoskeletal disorders also known as “cumulative trauma disorders,” “repetitive strain injury,” and “occupational overuse syndrome”, represent a set of pathological conditions that impair the normal function of the soft tissue of the musculoskeletal system, such as tendons, muscles, cartilage, ligaments, and nerves. Usually, in a single incident trauma, traumatic effects occur instantaneously (for example, cuts, bruises, lacerations, falls, etc) while in cumulative trauma, the effects develop over time (for example back pain, carpal tunnel syndrome, eye strain, etc). For example, MSDs do not include musculoskeletal injuries that are caused by accidents, such as a torn Achilles tendon that results from stepping in a hole. However, MSDs arise when musculoskeletal soft tissues are subjected to repeated physical stress, usually from repetitive movements, static postures, or continuous loading of tissue structures, which in turn causes gradually accumulating tissue damage.

The physical stresses that can contribute to or cause MSDs are called "risk factors” and product-related MSDs occur when the risk factors, which cause or contribute to musculoskeletal system pathology, namely, force, repetition, awkward postures, static postures, vibration, contact stress and extreme temperatures, are not minimized or eliminated. The initial symptoms of MSDs may include fatigue, discomfort, and pain; as tissue damage worsens, other symptoms, such as weakness, numbness, or restricted movement, may also appear. Examples of MSDs include Carpal tunnel syndrome, Epicondylitis, Herniated spinal discs, Tarsal tunnel syndrome, Tendinitis, Rotator cuff tendonitis, DeQuervain’s disease, Trigger finger, Low back pain, etc.

Even though MSDs are not life threatening and in fact some of them may be reversible, particularly if early intervention is provided, evidence however shows that these disorders are debilitating. They cause persistent and severe pain, lost worktime, reduction or loss of a person's normal functional capacity both in work tasks and in other of life's major activities, loss of productivity, and significant medical expenses. Where preventive action or early medical intervention is not provided, these disorders can result in permanent damage to musculoskeletal tissues, causing such disabilities as the inability to use one's hands to perform even the minimal tasks of daily life (e.g., lifting a child), permanent scarring, and arthritis.

Work-related MSDs currently account for one-third of all occupational injuries and illnesses reported to the Bureau of Labor Statistics (BLS) by employers every year. These disorders thus constitute the largest job-related injury and illness problems in the United States today. In 1997, employers reported a total of 626,000 lost workday MSDs to the BLS, and these disorders accounted for $1 of every $3 spent for workers' compensation in that year. Employers pay more than $15-$20 billion in workers' compensation costs for these disorders annually, and other expenses associated with MSDs may increase this total to $45-$54 billion a year.[95] This is a considerable sum.

There are different types of MSDs occurring in the work environment. A typical case is low back pain, which occurs amongst office workers. One factor affecting the occurrence of low back pain, the most prevalent and costly work-related MSD in the U.S., is the design of the office chair. Another prevalent MSD is that of the shoulders, such as tendinitis. In the U.S., the average cost of a claim for a shoulder disorder is $16,000.[96] In 1996, there were approximately 37,000 cases of work-related shoulder disorders. One extrinsic factor that contributes to shoulder disorders is the use of very high armrests, which elevate the shoulders, deviating them from a neutral posture.

An MSD affecting the wrist-enclosed median nerve is known as carpal tunnel syndrome (CTS). CTS is often the result of a combination of factors that increase pressure on the median nerve and tendons in the carpal tunnel. One of these factors is excessive exposure to vibration, say from use of hand tools. In 1998, an estimated three of every 10,000 workers lost work-time due to CTS. Half of these workers missed more than 10 days of work. The average lifetime cost of carpal tunnel syndrome, including medical bills and lost time from work, is estimated to be about $30,000 for each injured worker.

3.4.1 Ergonomic Risk Factors

Ergonomic risk factors are the factors that create a potential for inflicting injury on the person, whether in the long term or short term. Epidemiologic studies, laboratory studies, and extensive reviews of the existing scientific evidence by NIOSH and the National Academy of Science[97], shows that the following described ergonomic risk factors are most likely to cause or contribute to MSDs. Some of these factors also constitute risks of long-term injuries like pressure sores. The factors are:

1. **Force**. Force refers to the amount of physical effort that is required to accomplish a motion or task. Motions or tasks that require application of higher force place higher mechanical loads on muscles, tendons, ligaments, and joints. Motions involving high forces may cause muscles to fatigue more quickly. High forces also may lead to irritation, inflammation, strains and tears of muscles, tendons and other tissues. The force required

to complete a movement increases when other risk factors are also involved. For example, more physical effort may be needed when the speed or acceleration of motions increases, when vibration is present, or when a person is in an awkward posture. Force can be internal, such as when tension develops within the muscles, ligaments and tendons during movement. Force can also be external, as when a force is applied to the body, either voluntarily or involuntarily. Forceful exertion is most often associated with the movement of heavy loads, such as lifting heavy objects on and off a conveyor, delivering heavy packages, pushing a heavy cart, or moving a pallet. Hand tools that involve pinch grips require more forceful exertions than those that allow other grips, such as power grips.

2. **Repetition**. Repetition refers to performing a task or series of motions over and over again with little variation. When motions are repeated frequently (e.g., every few seconds) for prolonged periods (e.g., several hours, a work shift), fatigue and strain of the muscle and tendons can occur because there may be inadequate time for recovery. Repetition often involves the use of only a few muscles and body parts, which can become extremely fatigued while the rest of the body is little used.

3. **Awkward Postures.** Awkward postures refer to positions of the body (e.g., limbs, joints, back) that deviate significantly from the neutral position while a product is being used or tasks are being performed. For example, when a person's arm is hanging straight down (**i.e.**, perpendicular to the ground) with the elbow close to the body, the shoulder is said to be in a neutral position. Awkward postures often are significant contributors to MSDs because they increase the work and the muscle force that is required.

4. **Static postures**. Static postures (or "static loading") refer to physical exertion in which the same posture or position is held throughout the exertion. These types of exertions put increased loads or forces on the muscles and tendons, which contributes to fatigue. This occurs because not moving impedes the flow of blood that is needed to bring nutrients to the muscles and to carry away the waste products of muscle metabolism. Examples of static postures include gripping tools that cannot be put down, holding the arms out or up to perform tasks, or standing/sitting in one place for prolonged periods.

5. **Vibration**. Vibration is the oscillatory motion of a physical body. Localized or segmental vibration, such as vibration of the hand and arm, occurs when a specific part of the body comes into contact with vibrating objects such as powered hand tools (e.g., chain saw, electric drill, chipping hammer) or equipment (e.g., wood planer, punch press, packaging machine). Whole-body vibration occurs when standing or sitting in vibrating environments (e.g., driving a truck over bumpy roads) or when using heavy vibrating equipment that requires whole-body involvement (e.g., jackhammers).

6. **Contact stress**. Contact stress results from occasional, repeated or continuous contact between sensitive body tissue and a hard or sharp object. Contact stress commonly affects the soft tissue on the fingers, palms, forearms, thighs, shins and feet. This contact may create pressure over a small area of the body (for example wrist, forearm) that can inhibit blood flow, tendon and muscle movement and nerve function. Examples of contact stress include resting wrists on the sharp edge of a desk or workstation while performing tasks, pressing of tool handles into the palms, especially when they cannot be put down, tasks that require hand hammering, and sitting without adequate space for the knees.

7. **Extreme Temperature:**[98] Cold temperatures tend to reduce the dexterity and sensitivity of the hand. Cold temperatures, for example, cause the worker to apply more grip force to hold hand tools and objects. Also, prolonged contact with cold surfaces (e.g., handling cold meat) can impair dexterity and induce numbness. Cold is a problem when it is present with other risk factors and is especially problematic when it is present with vibration exposure. Warm temperatures cause moisture buildup, which can cause skin breakdown.

Of these risk factors forceful exertions, repetition, and awkward postures, especially when occurring at high levels or in combination, are most often associated with the occurrence of MSDs. Although some of the risk factors described above are easy to identify and it is not difficult to understand why they may be likely to create hazardous exposures, others are not as apparent or observable.

3.5 PRESSURE ULCERS

Pressure ulcers are injuries that develop on tissues overlying a bony prominence and which have been subjected to prolonged pressure against an external object such as a wheelchair seat, a bed, a cast or a splint. These injuries, also known as bedsores, pressure sores, trophic ulcers and decubitus ulcers occur most often in individuals with diminished or absent sensation or who are debilitated, emaciated, paralyzed, or long bedridden. Tissues over the sacrum, ischia, greater trochanters, external malleoli, and heels are especially susceptible.[99] An extrinsic risk factor for development of pressure sores includes unrelieved pressure usually emanating from body support systems. When tissues are compressed due to static positioning, capillary blood pressure can be so greatly increased that blood supply to and lymphatic drainage from the affected area become deficient. In the U.S., the total cost of pressure sore management in all settings is estimated at $1.335 billion.[100]

3.6 ERGONOMICS AND PRODUCT DESIGN

A well-designed product should be safe, efficient, comfortable and convenient to use, durable, serviceable, realistically priced and aesthetically pleasing.[101] Human factors apply to all except for price. Challenges of the global age emphasize resource conservation, pollution reduction and the right to mobility for all. To meet these challenges, adoption of a more user-centered (as opposed to product-function dominated) orientation is essential. User-centered design necessitates taking at the early stages of design, significant account of users, the tasks/activities they wish to perform and the context in which the activities will be performed. Currently, several methods and tools exist for incorporating ergonomics into product design. These are summarized in tables 3.1 and 3.2:

Table 3.1: Common ergonomics evaluation methods and techniques

Method/Techniques	**Purpose**	**Design Process Stage**
Checklists	Used to define operation of a product and identify user needs.	Early stage of the design process and field test.
Task Analysis	Defines and evaluates operational procedures of human/product/system	Conceptual design, final design and field test.
Focus group	Used to identify user issues and their importance.	Any stage of the design process.
User Interview	Identifies user needs.	Any stage of the design process.
Observation Method	Defines the dynamics of the artifact/system/environment	Final design stage.
Protocol Analysis	Evaluates a design, users' expertise levels and understand users' concept of product.	Any stage of the design process.

Table 3.2: Common ergonomics evaluation tools

Tool	Purpose	Design Process Stages	Existing Systems
Computer Aided Design Simulation and Virtual Reality (VR)	To evaluate design and its perceived use	Different design stages	Safework Pro by Delmia, 3D Static Strength Prediction (3DSSP) Tool by University of Michigan, ErgonLift by Dettmer, U., Schiffmann, M. and Laurig, W., SAMMIE by Portal el al., EDS JACK by EDS
Mock-up evaluation using real persons or mannequins	To evaluate product usage with users' participation.	Conceptual Design	
Prototype evaluation	To evaluate a design outcome under real conditions.	Different design stages	

3.6.1 Market Research

Usually, prior to the onset of product development, market research is conducted using such methods as questionnaires and field observations. The goal is to identify opportunities for development of new products and improvements of existing products. The research basically provides information on what people want and will buy at some future time. Information provided by market research is then utilized in the formation of design objectives related to cost, performance, ergonomics, reliability, etc. When these objectives are determined, the next step is to rank them. The ranking is considered when arbitration involving design trade-offs is required at a later time. For example, a trade-off decision in favor of safety over cost and aesthetics may be necessary when designing a safety critical device.

Market requirements, which define the nature of the product in some detail, follow from the design objectives and market research. These requirements are mostly qualitative in nature and include general functional and performance requirements and a description of specific features which the product should posses in order to satisfy the needs of the user. The requirements may also include design constraints.

Ergonomic activities associated with market research include development of user profiles, evaluation of existing products for safety and comfort, and conducting individual and group focused interviews. The focused interviews concentrate on topics such as user needs, user perception of alternative designs, the relative importance of specific features, and the criteria that consumers apply when evaluating different types of products.

3.6.2 User Profiles

Before the onset of formal product design, a profile of all product users needs to be developed to ensure that the eventual product is suitable for all users. The user profile is a summary of the characteristics of a product's intended users. Generally, the user profile contains the following information:

- Age
- Gender
- National origin
- Education
- Previous experiences with similar products

- Native language
- Literacy level
- Foreign language skills
- Physical abilities
- Sensory abilities
- Occupation
- Specialized skills
- Level of motivation

Of these, age, gender, and physical abilities affect strength capabilities while age, gender and national origin affect body size measurements of users. The information provided for each characteristic should include an indication of the variability among users. For items such as physical capability, an indication of the ability of the least capable expected user might be sufficient.

Designing for individuals with disabilities presents great challenges. People with disabilities may have reduced sensory and motor capabilities, limited cognitive ability, or emotional difficulties. The last two types of handicaps present the most difficult challenge to design. Also, disabled persons often lag behind the general population in areas of education and income and are usually older than the consumer population as a whole.

3.6.3 Design Constraints

Identifying design constraints as early as possible is very important since constraints limit the options available to product designers. In some cases they may even limit the practical feasibility of the product. Constraints affecting product design are:

- User-related
- Technological
- Cost and Schedule
- Regulatory
- Environmental

Ergonomics is primarily concerned with user-related constraints, that is, user limitations and capabilities; regulatory constraints, such as ergonomic standards and safety regulations, and; environmental constraints, such as restrictions imposed on the design and arrangement of controls and displays because of unusual environments. Technological constraints also affect ergonomics since limitations in technology might actually mean violation of user-related requirements.

3.6.3.1 User-Related Constraints Ergonomic design constraints associated with a product user consists of restrictions imposed by the physical capabilities of the users. Usually, user-related constraints are determined from the user profile information and the constraints are then used to impose limits on the design. Generally, constraints should be established so that the physical limitations of the least capable, say the 5th percentile user, is not exceeded. For example, gender information is important in determining strength requirements. Women, typically have significantly less strength than men for most muscle groups. Thus, strength requirements for pushing, pulling and lifting should not exceed that of the 5th percentile female.

There is great variation in the body characteristics of people. This has a significant impact in furniture design – desks and seating systems, especially when the design is for international markets. In fact, products designed to the anthropometry of Americans fit 90% of Germans, 80% of the French, 65% of the Italians, 45% of the Japanese, 25% of the Thais and 10% of the Vietnamese.[102] Variability in anthropometric measurements is addresses using *cases*.

It is crucial that physical capabilities and limitations of users be taken into consideration, more so if a design is to be used by those with say normal functioning motor skills and those with reduced function. A large male who has impaired motor skills in the hands may have difficulty operating an accessibility button which requires a great deal of force to operate while a small female with normal hand functions may have no problems operating the button to access a building with a stroller.

Extreme temperatures also impose constraints on both design and human performance. For example, in designing controllers for snow equipment, it is required that the controllers be larger and placed further apart than controls used only during mild temperatures. This is due to the fact that the operator usually wears heavy, bulky gloves, which reduces hand dexterity.

3.6.3.2 Variability of Body Sizes Body components of individuals occur in combinations of small, medium and large dimensions. Overall, there is no average man or woman. In order to capture body size variability in a target population, the relevant body dimensions are characterized as cases. A case represents a set of body dimensions, which a designer plans to accommodate.103 The case may be measurements from an actual person or measurements statistically generated to represent relevant body dimensions. Cases can be one dimensional or multidimensional. For example, in designing the height of the entrance to an aircraft, only a single body dimension, stature, is relevant. On the other hand in designing a seat cushion, the relevant dimensions are the buttock-popliteal length and hip breath. This latter case is two-dimensional. Three types of cases have been defined:

a) Central cases – usually located towards the center of the distribution of the body dimensions selected. Examples include the mean, median, and 50th percentile. A central case is applied when there is a need to center something and often serve as the starting point for scaling a design. Factors that determine the scaling factors are then arrived at using boundary point information or distributed point information. To create other sizes, a pattern that matches the central case is scaled using a grading process. This fitting process tends to be less costly than creating a new pattern for each case along the scaling line. However, for a design problem in which a multidimensional case is required, using a central case may mean that no real person exists whose combined body dimensions match the central case. The reason is that there is no individual that is average in every body dimension. So averaging the dimensions of different people may mean that no one is accommodated, especially when multidimensional cases are used.

b) Boundary cases – usually located towards the outer boundaries of the body dimensions selected. Examples include the minimum, maximum, 5th and 95th percentiles. When points towards the center of measurement distribution are not important, boundary cases can be used. For problems requiring multi body measurements, visualizing the multidimensional plot of the body measurements can be difficult. More so, when the dimensionality of the cases is less than it should be, the proportion of the population that is actually accommodated is likely to be less that that intended. Also, using only boundary cases may mean that cases in the center, which may be a major proportion, may not be accommodated.

c) Distributed cases – usually spread throughout the region of body dimensions to be accommodated. An example of application of these type of cases is height levels an adjustable seat can take, which represent the various sitting heights of individuals in the distribution. Use of distributed case can be expansive and time-consuming since many cases are used. However, since the cases are distributed across the entire region, the risk of missing a key area in the measurements is minimal.

3.6.3.3 Regulations and Standards Ergonomic regulatory constraints for product design have the primary objective of ensuring safety and comfort during product use. The ergonomic expert normally undertakes the responsibility for identifying relevant ergonomic standards and regulations and making sure that they are referenced in the appropriate product requirements documents. Regulations and standards pertaining to ergonomics occur at the international, national, and local levels and have the characteristic of being dynamic. As such, manufacturers must monitor these regulations and standards continuously since they significantly impact the acceptability of their current products and the design of future products.

Most ergonomic regulations are concerned with job design issues and management practice while standards address product design. Several ergonomic standards exist. One is the ANSI/HFS 100-1988 standard for computer workstations published by the Human Factors and Ergonomics Society and the American National Standards Institute (ANSI). Another is the ergonomic standard for military equipment, MIL-STD-1472D. This standard is encyclopedic, covering nearly every aspect on the interface between user and product. ANSI and the Rehabilitation Engineering and Assistive Technology Society of North America (RESNA) have provided standards for wheelchair design. Their standards guide the design of manual wheelchairs, power wheelchairs and scooters.[104]

3.7 KNOWLEDGE REPRESENTATION OF CONSTRAINTS

Design typically commences with a statement of customer needs, which is formally translated into product design specifications, usually short statements about customers' requirements. Based on the initial product design specifications, several design concepts are generated and a final concept is selected with respect to some measure. This final concept is significantly dependent on the requirements of the various design stakeholders VIZ ergonomics, manufacturing, assembly, supply chain, etc. Following concept generation, technical requirements of the product are established and then represented.

One way of representing design constraints is by use of algebra. Algebraic constraint representation has the benefit of being generic, rigorous and domain independent and thus is suitable for multidisciplinary engineering design and modeling. Another way is by using IF THEN rules. In this work, ergonomic considerations represented using algebra and IF THEN rules.

3.8 EXTENSIBLE MARKUP LANGUAGE (XML)

The Extensible Markup Language (XML) is a structured language for documents containing structured information that is, both content and some indication of what role the content plays. It is defined as an application profile of the Standard Generalized Markup Language (SGML). The XML specification defines a standard way to add markup to documents, the latter being a mechanism to identify structures in a document. Roughly speaking, XML, a restricted form of SGML was created so that richly structured documents could be used over the web. Neither the Hyper Text Markup Language (HTML) nor SGML can practically provide this capability. HTML comes bound with a set of semantics and does not provide arbitrary structure. SGML on the other hand, provides arbitrary structure but is too difficult to implement just for a web browser. Even though full SGML systems solve large complex problems that justify their expense, viewing structured documents sent over the web rarely carries such justification.[105]

XML documents typically are made up of markup and content. There are six types of markup that can occur in an XML document.[106] These are, elements, entity references, comments, processing instructions, marked sections, and document type declarations. These are described as follows:

1. **Elements:** Elements, delimited by angle brackets, usually identify the nature of the content, which they surround. An element that is not empty begins with a start-tag <element name> and ends with an end-tag, </element name>.

2. **Attributes:** These are name-value pairs that occur inside start-tags after the element name. Every attribute must be in quote. For instance, <element name = “weight”>
3. **Comments:** These usually begins with “<!--" and end with “-->”. Comments can be placed between markup, anywhere in an XML document. Comments are not part of the textual content of an XML document and as such an XML processor is not required to pass them along to an application.
4. **Marked Sections:** These are used to instruct a parser to ignore certain markup characters. An example is the CDATA section.
5. **Process Instructions:** Process instructions (PIs) are used to provide information to an application. Similar to comments, they are not textually part of the XML document though the XML processor is required to pass them to an application. PIs have the form “<?name pidata?>. “name” called the PI target, identifies the PI to the application. Applications would usually process only the targets they recognize. Names beginning with XML are reserved for XML standardization.
6. **Document Type Declarations:** Declarations allow a document to communicate meta-information to a parser about its content. Meta-information includes the allowed sequence and nesting of tags, attribute values with their types and defaults, the names of external files that may be referenced and the entities that may be encountered. There are four types of declarations in XML: element type declarations, attribute list declarations, entity declarations, and notation declarations. Element type declarations identify the names of elements and the nature of their content. Attribute list declarations identify elements, which are allowed to have attributes, the value of these attributes and their default value. Entity declarations allow for a name to be associated with some other fragment of

content. The content could simply be regular text, a chunk of document type declaration, or a reference to an external file containing either text or binary data.

4.0 PROPOSED METHODOLOGY

The methodology that is proposed in this dissertation is described below. Section 4.1 illustrates the classification and coding system and in the following sections, the knowledge representations of the rules of physical ergonomics are described.

4.1 DESCRIPTION OF PROPOSED METHODOLOGY

The method proposed in this dissertation for making considerations for physical ergonomics at the conceptual stage of computer-aided product design is comprised of three sequential modules:

Module 1 Categorization of Discrete Products for Ergonomic Considerations: Categorization of objects promotes efficient interaction with these objects in terms of accessing them and retrieving their information. Product categorization therefore saves time. Here, a classification and coding (C&C) system is applied in grouping discrete products according to the similarities they share for ergonomic considerations. Ergonomic considerations, significant to a product's design are dependent on the functions, which users of the product will perform on them. These functions are known as product functions.[107] For example, to drink from a mug, a user will first grasp the mug with his/her hand or fingers, lift the mug to the lips, grasp the rim with the lips and then drink from the mug. Thus, the task of drinking from a mug can be grouped into two main tasks – grasping tasks & displacement tasks. These tasks (user functions), determine ergonomic considerations that hold for the mug and generally, for any products that people will grasp and displace. Some of these considerations are to limit interface pressure and to reduce moisture build up in person-product interface.

Module 2 Ergonomic Constraint Representation: In module 1, the C & C system is used to derive ergonomic constraints that govern each product category. The implementations of these constraints are next obtained from literature. For instance, assuming that the product being designed will be displaced by the users, the consequence of this user action is that forceful exertions experienced by the user must be kept within safe limits. For example, limiting the weight of a product is one way to ensure that forceful exertions experienced by a person who will displace the product are kept within safe limits. In literature, NIOSH provides the weight constraint for products which users will manually handle at certain frequencies and for certain durations of time. When such information has been acquired, it is then represented in computable form so that it can easily be integrated into a CAD environment. In this work, the formats used for constraints representation are algebra and IF THEN rules.

Module 3 Propagation of Ergonomic Constraints to Downstream Design Activities: To ensure that ergonomics is taken into consideration during the generation of design alternatives and in the determination of the characteristics of the final product, it is necessary that ergonomic constraints be propagated to downstream design activities. Here, constraint propagation is achieved by the use of Extensible Markup Language (XML) technology. Figure 4-1 shows a conceptual view of the method described.

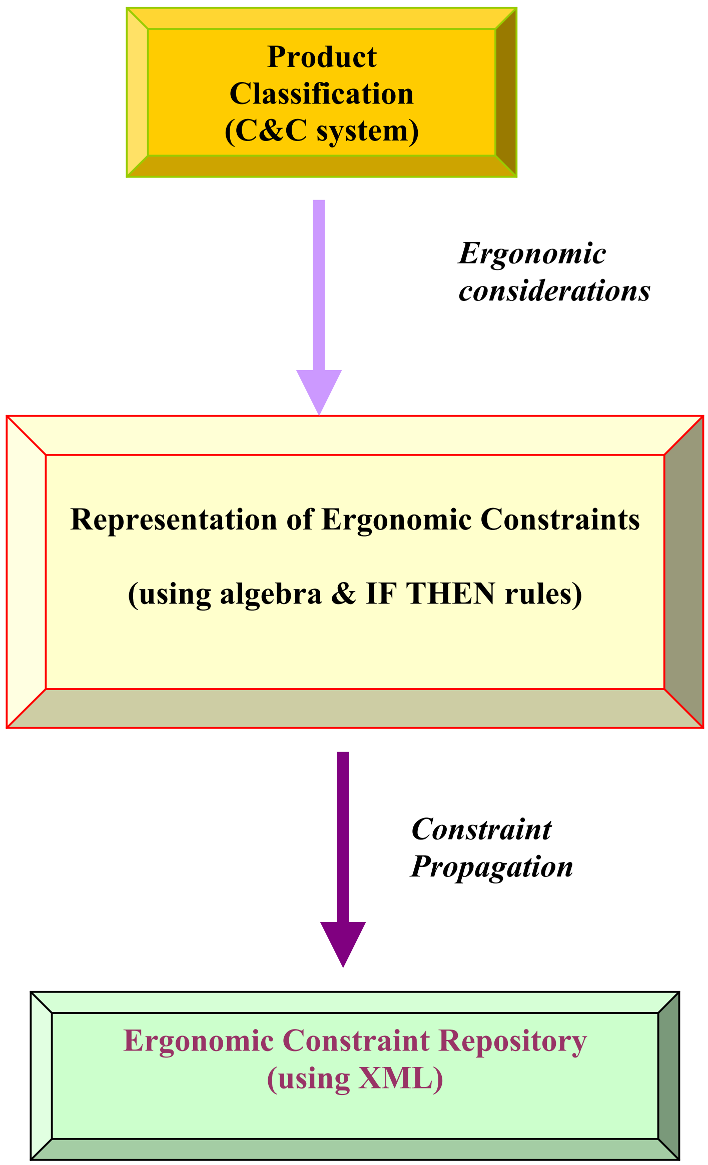

Figure 4-1 Conceptual view of proposed methodology

4.2 A CLASSIFICATION AND CODING SYSTEM FOR MAKING ERGONOMIC CONSIDERATIONS

There are hundreds of thousands of everyday products – from screws and pens to washing machines. On each of these products, certain ergonomic considerations must be made to promote safety and comfort during person-product interaction. To efficiently and concisely capture ergonomic design rules relevant to the great variety of products, a C&C system is presented in this work for making considerations for physical ergonomic. The system uses the concept of group technology[108] to categorize discrete manufactured products based on similarities of ergonomic principles that should govern their design. For example, every product that a person will make contact with, must take interface pressure resulting from the contact into consideration. The advantage of a C&C system is that it is concise and therefore lends itself to implementation in a computing environment. The C&C system is described below.

4.2.1 Construction of the Classification and Coding System

The first step in constructing the taxonomy is to determine when each of the principles of physical ergonomics needs to be taken into consideration (table 4-1). A description of each of these principles was previously presented in chapter 2. The aforementioned, then lays the foundation for constructing the taxonomy. The code for the C&C system is generated and illustrated in table 4-2.

Table 4-1 Scenarios for applying rules of physical ergonomics

Rules	When to apply
Reduce contact pressure & tissue distortion	• Whenever a person will make physical contact with a product
Reduce moisture accumulation in person-product interface	• Whenever a person will make physical contact with a product
Reduce heat buildup in person - product interface	• Whenever a person will make physical contact with a product
Limit shear Force	• Whenever a person will make physical contact with a product • When a person will move against a surface
Limit body motions	• When a person will move his/her body to operate a product
Limit forceful body exertions	• When a person will need to displace an object
Limit static load	• When a person will maintain an unchanging body posture for long periods
Afford body postures of least stress	• Whenever there will be physical contact between a person and a product • Whenever a person will need to assess a location within, or external to a product, without making physical contact
Clearance	• Whenever a person and a product will move while in physical contact • Whenever a person will need physical assess to a location within a product • Whenever a person will need physical assess to a location external to the product while interacting with the product
Forceful impacts	• Whenever a person and a product will move while in physical contact
Vibration	• Whenever a person will make physical contact with a product while the product is power operated

Table 4-2 Code for Classification & Coding system

Digit	Value	Ergonomic Considerations
1	0 – no physical contact	-
	1- only rest on product	Contact pressure, tissue distortion, moisture and temperature buildup, shear in person-support surface interface, clearance for the body to access rest surface
	2 – only grasp product	Contact pressure, tissue distortion, moisture and temperature buildup, shear in person-grasp surface interface, clearance for the body to access grasp surface
	3- only wear product	Contact pressure, tissue distortion, moisture and temperature buildup, shear in person-product interface, clearance to wear product
	4- rest on product + grasp product	Contact pressure, tissue distortion, moisture and temperature buildup, shear in person-support surface interface and in person-grasp surface interface, clearance
	5- rest on product + wear product	Contact pressure, tissue distortion, moisture and temperature buildup, shear in person-support surface interface and in the interface between the person and the product to be worn, clearance
	6- grasp product + wear product	Contact pressure, tissue distortion, moisture and temperature buildup, shear in person-grasp surface interface and in the interface between the person and the product to be worn, clearance
	7- rest on product + grasp product + wear product	Contact pressure, tissue distortion, moisture and temperature buildup, shear in person-support surface interface, in the person-grasp surface interface and in the interface between the person and the product to be worn, clearance
2	0-user will not retain the same body posture for a long time	-
	1- user will retain the same body posture for a long time	Static load
3	0 – entire product will not be displaced	-
	1- displace entire product using tactile force	Forceful exertion due to tactile force applied to displace entire product
	2- displace entire product using air pressure	Forceful exertions due to air pressure applied to displace entire product

(Table 4-2 cont'd)

4	0 – no component displacement	-
	1- displace product component using tactile force	Forceful exertion due to tactile force applied to displace product component
	2- displace product component using air pressure	Forceful exertions due to air pressure applied to displace product component
5	0 – product does not have any component to be accessed without physical contact	-
	1- user will access an internal location w/o touching it	Posture of least stress during access to internal location, clearance to location to be accessed
6	0 – product does not have any component to be operated by body motions	-
	1- operate by body motions	Repetitive body motions
7	0 – product will not have any component with which a user will make physical contact while being power-operated	-
	1- touch product or component while power-operated	Vibration exposure

(Table 4-2 cont'd)

8	0 – product will not have any component with which a user will make physical contact during person-product ambulation	-
	1- person and product will ambulate while in physical contact	Clearance for the body to clear obstacles, forceful impacts
9	0 – will not rest on product during interaction with external objects	-
	1- user will interact with external objects while in physical contact with product	Postures of least stress during interaction with external objects, clearance to locations to be interacted with
10	0 – no physical contact with product	-
	1- user will move against product	Shear force in the interface between the person and the surface to be moved against

4.2.2 Example of How to Apply Classification and Coding System

To illustrate the use of the C&C system, assuming a designer wishes to determine what ergonomic rules apply to a 'Styrofoam cup' for drinking beverage, the designer will need to go through the following steps:

1. Specification of design concept

- Styrofoam cup for drinking beverages
- Cup will not have a grip

2. Tasks to be performed ***on*** the design concept (this should be determined using *task analysis*)

- Cup will be grasped in either hand
- Cup will be displaced in order for user to drink beverage

3. Determination of product code from table 4-2

- Product code is 2010000000
- Make considerations for contact pressure, tissue distortion, moisture and temperature buildup, shear in person-grasp surface interface, and adequate clearance
- Make considerations for forceful exertion due to tactile force applied to displace product

4.3 KNOWLEDGE REPRESENTATION OF ERGONOMIC CONSIDERATIONS

In the following, a sample of ergonomic considerations are represented in a general format. To obtain ergonomic specifications for a product, values for the variables are then obtained from literature to fill in the general models.

4.3.1 How To Limit Interface Pressure And Tissue Distortion

Pre-contouring a contact surface, using the user's body weight, shape, size, posture and muscle tone, is one way to reduce interface pressure and tissue distortion. Also, using material that will allows the body be immersed in it, will promote pressure relieve and lessen distortion to tissues in the area of contact. For devices that support the body, the orientation of the support surfaces, can be used to redistribute interface pressure. In a sitting context, ensuring that a person sits at his/her popliteal height, that the support surface covers the entire area of the body that will rest on it while avoiding contact with body locations most sensitive to pressure, will promote pressure relief.

4.3.1.1 Knowledge Representation of Rules in Computable Form (Interface pressure & Tissue distortion) - Pre-contouring a surface

Let

f_{per} = function defining a person's body contour and which minimizes interface pressure and tissue distortion. This function is dependent on body weight, size, posture, and muscle tone.

f_s = function defining the contact surface having a certain stiffness, s

To reduce interface pressure and tissue distortion

$$f_{\text{s}} \cong f_{\text{pers}} \tag{4-1}$$

2. Using appropriate material stiffness to allow the body be immersed

Let

S_{per} = material stiffness required for an object with which a person or population having body weight, w, and body posture, p, will make physical contact,

S = stiffness of a contact surface

S_{min}, S_{max} = min and max stiffness of contact object for limiting interface pressure and tissue distortion

To reduce interface pressure,

$$S_{min} \leq S \leq S_{max} \qquad (4\text{-}2)$$

Also,

3. Using orientation of support surfaces

a) Sitting context

Consider figures 4-2 a& 4-2b

Let

S = surface that supports the upper body, buttocks and lower legs in a sitting posture,

T, U = pivot axes

S_1 = surface that supports the upper body,

S_2 = surface that supports the buttocks/upper legs

S_3 = surface that supports the lower legs

H_p = a user's popliteal height, sitting

H_L = length of legrests

L_f = length of footrest

L_u = length of user's feet

H = length between the posterior seat surface edge and the surface on which the feet rest

h_f = height of footwear

L, W = length and width of seat, respectively

W_p = max width of user's hips

L_{bpl} = buttocks popliteal length of user

C_1 = clearance to avoid pressure point behind the legs

n = # of angular orientations S can assume

n_1 = # of angular orientations S_1 can assume

n_2 = # of angular orientations S_2 can assume

n_3 = # of angular orientations S_3 can assume

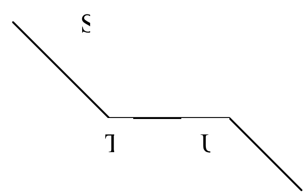

Figure 4-2a Illustration of sitting context 1

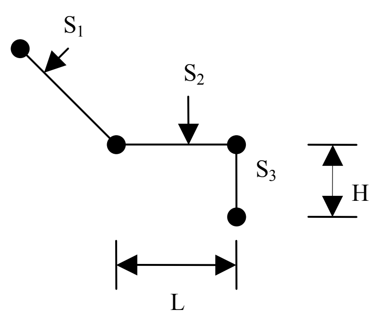

Figure 4-2b Illustration of sitting context 2

To promote pressure relief to the sitting bones,

$$W \geq W_p \tag{4-3}$$

$$L = L_{bpl} - C_1 \tag{4-4}$$

$$H = H_p + h_f \tag{4-5}$$

$$n \geq 2 \tag{4-6}$$

$$n_1 \geq 2 \tag{4-7}$$

$$n_2 \geq 2 \tag{4-8}$$

$$n_3 \geq 2 \tag{4-9}$$

If legrests are used,

$$L_f = L_u + h_f \tag{4-10}$$

4.3.2 How To Limit Shear and Friction Forces

During sitting, shear force can be minimized by inclining the thigh support slightly above the horizontal to match the necessary angle of backrest-recline (figure 2.1). Using material, which is thin, flexible and stretchable, also helps minimize friction in the person-support surface interface, and thus to lessen tissue damage due to shear.

4.3.2.1 Knowledge Representation of Rules in Computable Form (Shear & Friction forces)

1. For body supports

Let

M = material of the body support's cover

If product will reduce shear and friction force THEN

M should be thin, flexible and stretchable (4-11)

2. For body supports used in ambulatory sitting context

Let

S_2 = surface that supports the thighs/buttocks during sitting

σ = angle of inclination of S_2 above the horizontal

Thus,

If shear and friction forces are to be reduced, THEN S_2

should be inclined at σ above the horizontal plane during ambulation (4-12)

4.3.3 How to Reduce Static Load

Static load can be reduced in a sitting context by incorporating clearance on the seat surface for postural changes and also affording adjustability of body supports surfaces. Providing armrests during sitting also helps to reduce static load to the upper body.

4.3.3.1 Knowledge Representation of Rules in Computable Form (Static load)

1. Seat surface clearance for postural changes on

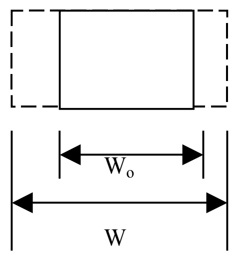

Figure 4-3 Illustration of clearance for postural changes

Consider figure 4-3 and let

W_0 = original length of seat surface

W = new length of seat surface

C_2 = clearance required to enable postural change (usually 2.5cm)

To limit static load,

$$W = W_0 + C_2 \tag{4-13}$$

2. Allowing postural orientation changes for body supports

Consider figure 4-2b

Let

S_1, S_2, S_3 be body support surfaces in a sitting context for the upper body, upper legs and lower legs respectively

Φ_1, Φ_2 = range of adjustability of S_1

ψ_1, ψ_2 = range of adjustability of S_2

To limit static load on the body,

If static load is to be reduced THEN

S_1 should be adjustable between Φ_1, Φ_2 AND

S_2 should be adjustable ψ_1, ψ_2 [109] (4-14)

3. Use of armrests

Let

H_a = armrest height,

H_e = elbow height sitting, of user

To reduce static load,

$$H_a = H_p \quad (4\text{-}15)$$

4.3.4 How to Reduce Forceful Body Exertions

Forceful exertions can be kept safe by ensuring that the amount of force required by a person to displace an object is within acceptable limits when the frequency, duration, direction and point of application of the force is taken into account as well as the posture in which the person will apply the force.

4.3.4.1 Knowledge Representation of Rules in Computable Form (Forceful exertions)

Let

P = personal factors of a person to manually handle a load which are age, gender, body size, body component to handle load, posture, muscle strength, endurance in dynamic conditions, training, fitness, experience, skills,

E= environmental factors that influence load handling which are climatic, altitude, and terrain

T = task requirements for accomplishing a task, which are speed/frequency, continuous/discrete, duration, point of application and direction of application of force/torque, displacement required and the path of motion. Also whether the task will be performed under static or dynamic (active light or heavy dynamic) body conditions and whether there will be static or dynamic coupling between the body and the product are other task factors to be considered.[110, 111, 112, 113]

1. Displacing entire products

Let

W = weight of product to be displaced

W_m = maximal acceptable weight of product to be displaced by a person under conditions P, E and T

To keep forceful exertion safe,

$$W \leq W_m \tag{4-16}$$

2. Displacing product components

Let

R = resistance to displacement an object presents at location L at which it will be displaced, under factors E, and task factor, T,

d = amount of displacement desired,

F_m = maximal acceptable force/torque a person can apply based on P, E and T

F = force required to displace product by an amount, d

$$R = F / d \tag{4-17}$$

If a person with factors, P should safely displace the load over a distance, d

$$F \leq F_m \tag{4-18}$$

But,

$$F = R\,d \qquad (4\text{-}19)$$

Thus

$$Rd \leq F_m \qquad (4\text{-}20)$$

3. Portable products carried by a single hand, at the user's side, using a single handle[114]

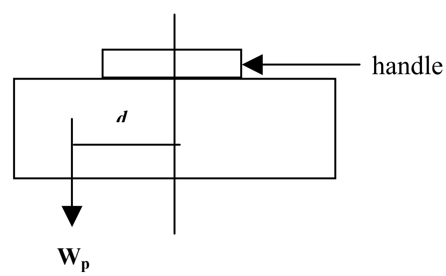

Figure 4-4a Illustration of forward loading

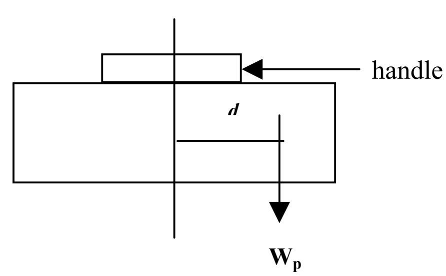

Figure 4-4b Illustration of rearward loading

With respect to figure 4-4a and 4-4b,

Let

W_p = weight of a product, P, to be carried by one hand,

d = distance from a line which extends directly downwards from the carry handle to the location of center of gravity,

M = moment about the handle, and

M_f and M_r = maximal allowable moments about the handle for forward and rearward loading respectively.

Then

$$W_p \quad * \quad d \quad = \quad M \qquad (4\text{-}21)$$

To minimize excessive force for forward loading,

$$M \quad \leq \quad M_f \qquad (4\text{-}22)$$

That is,

$$W_p \quad * \quad d \quad \leq \quad M_f \qquad (4\text{-}23)$$

$$d \quad \leq \quad M_f / W_p \qquad (4\text{-}24)$$

To minimize excessive force for rearward loading,

$$M \quad \leq \quad M_r \qquad (4\text{-}25)$$

That is,

$$W_p \quad * \quad d \quad \leq \quad M_r \qquad (4\text{-}26)$$

$$d \quad \leq \quad M_r / W_p \qquad (4\text{-}27)$$

4. Handle design of portable and transportable products

Let

L = length of handle

L_m = minimum recommended length of handle

C = clearance about handle with or without gloves

C_m = minimum recommended clearance about handle with or without gloves

D = diameter of grip area based on user's gender[115]

μ = coefficient of friction of grip surface (surface should be non-slip)

To improve product portability and reduce forceful exertions,

$$L \geq L_m \tag{4-28}$$

$$C \geq C_m \tag{4-29}$$

$$\mu > 1 \tag{4-30}$$

[116]

$$D > 20\text{mm (for men)} \tag{4-31}$$

[117]

$$D > 25\text{mm (for women)} \tag{4-32}$$

[118]

4) Minimize excessive force due to product size

Let

L_p, W_p, and D_p be the maximum length, width and depth of a product, respectively,

Lm_i, Wm_i, and Dm_i be the maximum allowable length, width and depth of a product, respectively, for a particular context i.

where

i = [one-hand portable/transportable; two-hand portable/transportable]

Then, to limit occurrence of excessive force due to product size,

$$L_p \leq Lm_i \tag{4-33}$$

$$W_p \leq Wm_i \qquad (4\text{-}34)$$

$$D_p \leq Dm_i \qquad (4\text{-}35)$$

4.3.5 How to Promote Body Postures of Least Stress

To promote body postures of least stress during sitting, it is necessary that the natural 'S' curve of the back be maintained, the backrest permit inclination behind the horizontal and that the distance from the edge of the seat to the footrest surface, be equivalent to the sitter's popliteal height. Use of cervical and lumbar support also promote postures of least stress. [119,120]

4.3.5.1 Knowledge Representation of Rules in Computable Form (Postures of least stress)

1. Sitting context

Let

S_1 = surface that supports the back while seated,

S_2 = surface that supports the buttocks/upper legs while a person is seated,

S_3 = surface that supports the feet while seated, which is parallel to the sole of the feet

H_p = a user's popliteal height, sitting

H = vertical height of the seat surface edge (posterior) from the surface on which the legs rest

R = range of adjustability of S_1,

φ = Min backrest inclination from the vertical, anticlockwise

ϕ = Max backrest inclination from the vertical, anticlockwise

h_l = height of lumbar support above seat surface,

hl_{min} = Min lumbar support height above seat surface,

hl_{max} = Max lumbar support height above seat surface,

d_l = depth of the lumbar support behind the front of the seat,

d_{min} = Min lumbar support depth behind the front of the seat,

d_{max} = Max lumbar support depth behind the front of the seat,

h_c = height of cervical support above seat surface,

hc_{min} = Min cervical support height above seat surface, and

hc_{max} = Max cervical support height above seat surface

C = height of footwear

Thus to support body posture of least stress,

$$\varphi \leq R \leq \phi \quad (4\text{-}36)$$

$$hl_{min} \leq h_l \leq hl_{max} \quad (4\text{-}37)$$

$$d_{min} \leq d_l \leq d_{max} \quad (4\text{-}38)$$

$$hc_{min} \leq h_c \leq hc_{max} \quad (4\text{-}39)$$

$$H = H_p + C \quad (4\text{-}40)$$

5.0 APPLICATION OF METHODOLOGY

In order to illustrate the methodology described in the preceding chapter, the design of a wheelchair seating system is hereby undertaken. Section 5.1 presents background information on wheelchair seating systems. Section 5.2 demonstrates the application of the proposed methodology to the design of a seating system. Section 5.3 describes the process through which the software application designs the seating system. Section 5.4 illustrates the XML container for propagation of constraints to downstream design activities.

5.1 THE WHEELCHAIR SEATING SYSTEM

The seating system of a wheelchair provides support to its user in a seated posture. A seating system may be comprised of a seat (cushion), backrest, armrests, legrests and sometimes, a headrest. Depending on the needs of the user, some or all of these components may be present and in different configurations. For example, individuals requiring postural changes by reclining in their wheelchairs will need headrests while individuals having good trunk control and living actively will require low backrests. Figure 5-1 shows a wheelchair and its seating system.

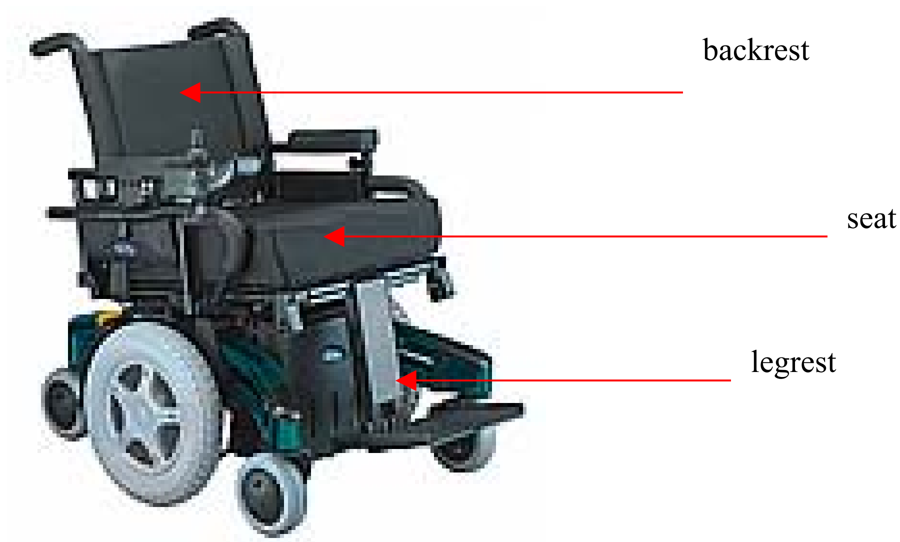

Figure 5.1 A wheelchair showing its seating system components (courtesy of Invacare)

5.2 DESIGN OF THE WHEELCHAIR SEATING SYSEM

For the implementation of the methodology presented in this work, the seating system to be designed will comprise a backrest, a seat, footrests and armrests, only. The tasks a user will perform ***on*** this seating system will be to ***rest*** on it. Using the C &C system given in table 4-2, the product code is obtained along with the ergonomic considerations relevant to the design concept. The knowledge representations of these considerations are then used to translate them into design specifications. The process just described is summarized below and the corresponding graphic user interfaces (GUIs) used in the computer implementation, are also shown.

- Design concept: - Wheelchair seating system, comprising a backrest, seat, footrests, and armrests
- Tasks to be performed on the seating system: - Rest on the seating system for a long time
- Product Code: - 1100000000
- Ergonomic considerations relevant to product concept:- Consider contact pressure, tissue distortion, moisture/temperature buildup, and shear in person-support surface interface. Also consider reduce static load occurring from sitting for prolonged periods and provide clearance to sitting surface
- Anthropometry being applied: – By Gordon et al. [121] The target users of the wheelchair seating system are U.S. males having 50th percentile weight (78.5kg), hip breath sitting, (37 cm), buttocks-popliteal length, (50 cm), popliteal height,

(43.4 cm), elbow height sitting, (23.1cm) . Footwear clearance (C) of 2.5cm is assumed.

5.2.1 Generating Ergonomic Constraints for the Seating System

1. To reduce interface pressure and tissue distortion

Foam stiffness is measured in indentation load deflection (ILD). ILD is a measure of the force required to indent a foam support by 25 percent of its thickness. When the primary function of a foam cushion is pressure relief, its ILD should generally lie within 30 - 50 pounds. [122, 123] Different authors have provided empirical models of seat contour shapes that relieve interface pressure. [124,125,126] However, for simplicity, only constraint on cushion stiffness is generated in this example.

From equation 4-2,

$$30\ ILD \leq \quad S \quad \leq \quad 50\ ILD \tag{5-1}$$

From 4-3, height of the posterior edge of the seat surface to the footrest surface is

$$H = H_p + h_f = 43.4 + 2.5 = 45.9 \text{ cm} \tag{5-2}$$

Length of legrests, H_L

$$= H = 45.9 \text{ cm} \tag{5-3}$$

$$W \geq W_p = 37 \text{ cm} \quad (5\text{-}4)$$

Seat length is

$$L = L_{bpl} - C_1 \quad (5\text{-}5)$$

C_1 is assumed 2.5 cm

$$= 50 - 2.5 = 47.5\text{cm}$$

2. To reduce static load (equations 4-11 to 4-13)

Armrests height, sitting is

$$H_a = H_e = 23.1\text{cm} \quad (5\text{-}6)$$

Seat width is

$$W = W_0 + C_2 = W_p + C_2 \quad (5\text{-}7)$$

C_2 is assumed 2.5 cm

$$= 37 + 2.5 = 39.5 \quad (5\text{-}8)$$

5.3 GRAPHIC USER INTERFACES IN COMPUTER IMPLEMENTATION

The first graphic user interface (GUI) is used to gather information from the designer in order to categorize the product and subsequently derive the product code (table 4-2). This code is used to obtain ergonomic considerations that are necessary for designing the product concept for ergonomics. The second GUI is used to obtain information from the designer on the nature of the contact the user will make with the product being designed. The third GUI allows the designer specify the anthropometric information of the users of the product. This information is applied in deriving design specifications. An output window is then finally presented to the designer with the ergonomic requirements for the design concept. The specifications are also saved to an XML file for propagation to a CAD environment.

5.3.1 Graphic User Interface 1

In this GUI, the following questions, which are based on the C & C system, are posed to the designer. Hints are also provided as a guide.

1. Will user touch this product (hint: sit on it, grasp it, lie on it) ?
2. Will user retain the same body posture for a long time (hint: sit for a long time, grasp for a long time)?
3. Will user need to displace entire product (hint: move a cell phone, push a wheelchair)?
4. Will user need to displace a component of the product (hint: lift the cover of a cell phone, move a joystick)?
5. Will user need to access an internal location of the product without physically touching it (hint: look at a monitor, talk into a mic)?
6. Will user operate any part of this product using body movements (hint: blink eye, nod head)?
7. Will user touch any part of this product while that part is power-operated (hint: electric hair clipper, automobile seat)?
8. Will person and product ambulate while in physical contact (wheelchair, automobile)?
9. Will user need to interact with locations, external to this product while remaining in physical contact with product (hint: reach a desk top)?

10. Will user move against product (hint: slide on it to transfer)?

Based on the Designer's selections on this GUI, GUI-2 will prompt for more information. In the case of the seating system example, the user will only "touch" the product. As such, in GUI-1, the answer to question 1 (Q1), is positive while that to every other question is negative.

Figure 5-2 Graphic user interface 1

5.3.2 Graphic User Interface 2

In this GUI, the software will prompt the designer to enter the nature of physical contact between the user and the product. The designer can only answer '**yes**' to a question if all conditions are met. For instance, if a the design concept was a coffee mug, in which case a user will only need to grasp the product, the answer to question 2 (Q2, GUI-2) will be positive while that to every other question will be negative. On the other hand, if the design concept is a chair that will use a hand-held controller, the designer will answer ‘yes’ to question 4 (Q4) and ‘no’ to all others. The questions are listed below:

1. Will user only rest on this product (hint : sit on it)?
2. Will user only grasp product?
3. Will user only wear product?
4. Will user rest on product **AND** also grasp it?
5. Will user rest on product **AND** also wear it?
6. Will user grasp this product **AND** also wear it?
7. Will user rest on product **AND** also grasp the product **AND** also wear this product ?

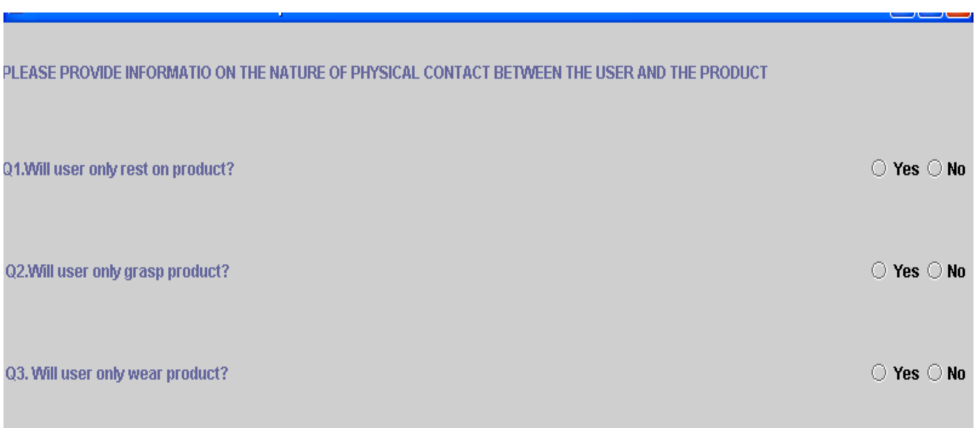

Figure 5-3 Graphic user interface 2

5.3.3 Graphic User Interface 3

The primary function of this user interface is to prompt the designer for information on what part of the user's body will rest on the product. This step is very important since it applied in "case selection", which essentially means, determining the components of the user's body that are relevant to the design concept. This information is used to extract anthropometric data from a database. GUI-3 is shown below.

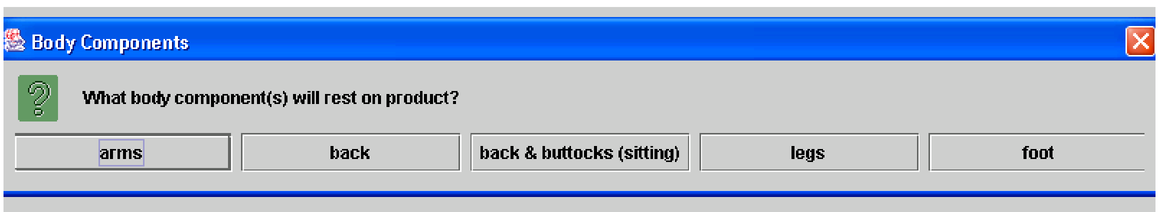

Figure 5-4 Graphic user interface 3

5.3.4 Graphic User Interface 4

This GUI prompts the designer for the population percentile of the different body components that are necesary for designing the seating system. The GUI is shown below.

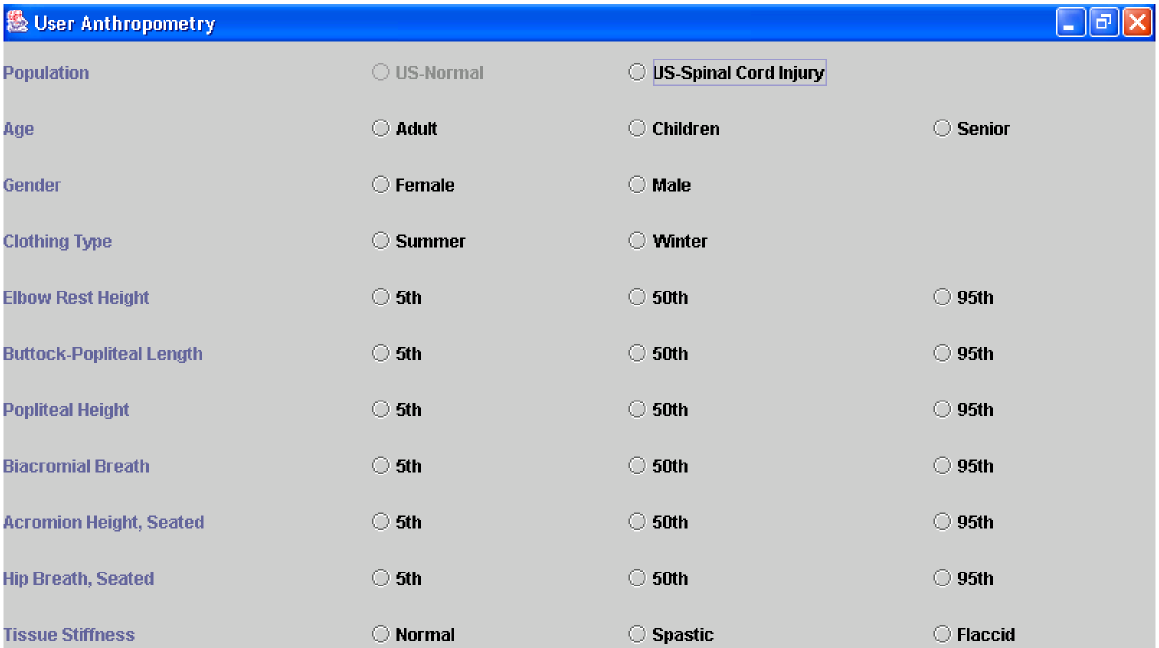

Figure 5-5 Graphic user interface 4

5.3.5 Output Windows

In these windows (figures 5-6 & 5-7), design specifications for the design concept are listed and also ergonomic considerations that govern the design concepts. References are also provided from literature to support the results.

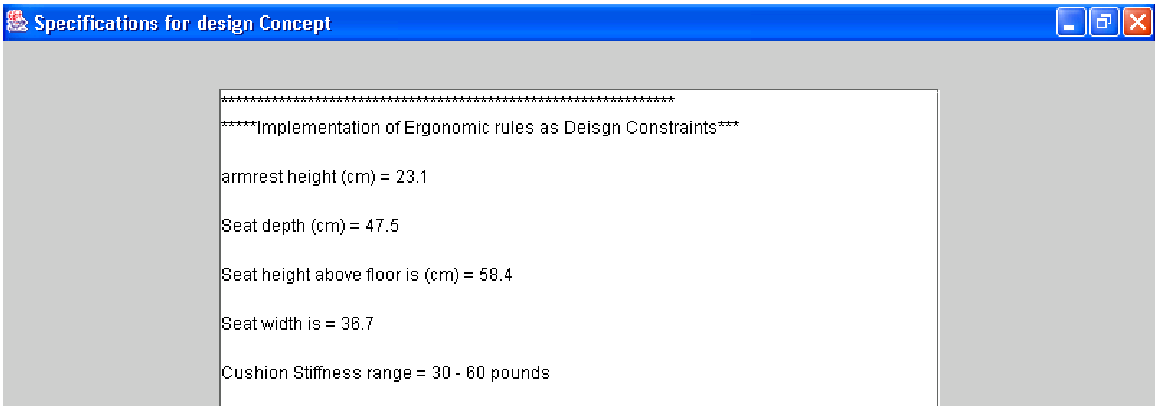

Figure 5-6 Output window 1

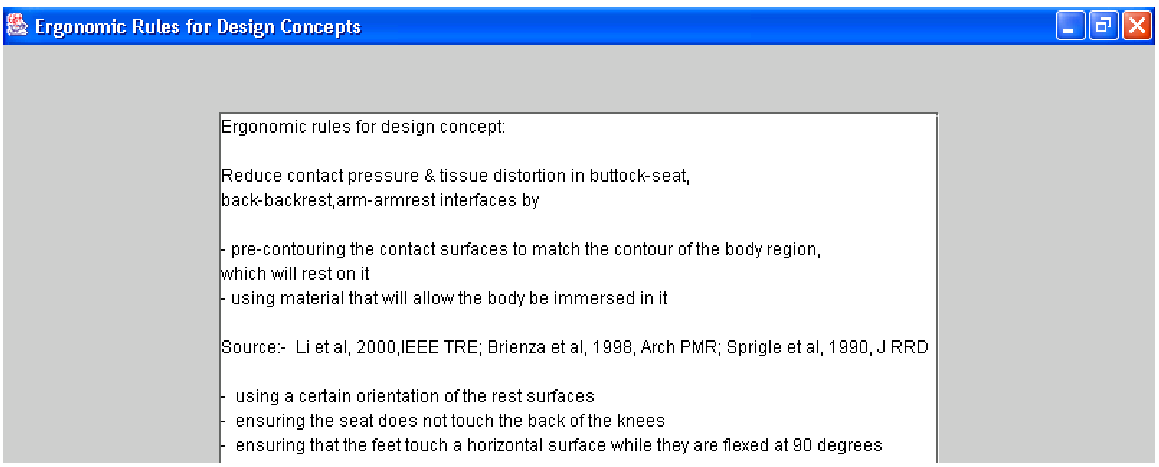

Figure 5-6 Output window 2

5.4 PROPAGATION OF ERGONOMIC DESIGN CONSTRAINTS

The following XML information repository (figure 5-7) is used to propagate the above-determined ergonomic constraints to downstream design activities.

```
<?xml version="1.0"

        <DOCTYPE note [……………..]>

<Ergonomic Design Container>

  <Ergonomic Considerations>

        Minimize interface pressure, tissue distortion, shear and friction, moisture and
        temperature buildup in  person-support interface
        Minimize static load

                </Ergonomic Considerations>

        <Ergonomic Constraints>
        <units> cm </units>
        <seat length>
                47.5
                </seat length>
        <seat width>
                37
        </seat width>
        .
        .

                </Ergonomic Constraints>

</Ergonomic Design Container>
```

Figure 5-7 XML container for wheelchair cushion propagation

6.0 TEST OF HYPOTHESIS

At the onset of the work conducted here, questionnaires were sent to designers to determine what current method they applied towards integrating ergonomics into design concepts. Five designers in the wheelchair manufacturing industry responded to the questionnaire. All five designers indicated they consulted the internet, journal materials and library text in order to obtain ergonomic information. Four designers indicated that the current process of locating information was somewhat difficult and the same number also indicated that they would like a computer-aided tool that will guide ergonomic design. All designers used anthropometric tables, 3D evaluation tools and design recommendations. All designers thought that a computer-aided tool that will provide ergonomic information early in design, would reduce design cycle time.

The hypothesis of this dissertation is that the computer aided ergonomic tool for conceptual design, developed in this work, will reduce design cycle time. This is based on the fact that it generates ergonomically constrained specifications for design concepts at the conceptual stage of product design.

6.1 METHODOLOGY

To test the above hypothesis, two designers were consulted, both in the wheelchair manufacturing industry. Since the designers were located outside the Pittsburgh area, the test was posted online. There were timers built into the software to determine the time it took them to perform the test. Before taking the test, the designers received an explanation of how the ergonomic tool developed here worked. They were not allowed to interact with the tool before the test since that will provide answers to the test. The test is outlined below:

6.2 TEST DETAILS

6.2.1 First Online Screen

Thank you for taking the time to evaluate this ergonomic tool. There will be two parts to the evaluation:

<u>Part I</u>

You will need to design a product for two different populations. You may use anthropometric tables, 3D evaluation tools and/or design recommendations. You may also consult any sources you wish.

Part II

You will need to use my ergonomic tool to design the same product.

The goal is to determine whether the method applied in Part I is better than that applied in Part II in terms of time and accuracy of results.

You will be timed for each test!!

Please click on the link "Test", below to begin Part I. The 'start' and 'stop' time will be noted by the program. Good luck!

TEST (hyperlinked to the next page)

6.2.2 Second Online Screen

Part I

First, open a word processor (Notepad or MS Word) to type in answers

Next, click the 'Start' button *BEFORE* viewing the Test below.

Please DO NOT view test before clicking 'START'.

Design Concept Description:- A product the user will sit on for prolonged periods

Test

1. Specify the dimensions for the backrest, seat and armrests of a seating system which a male, having *50th percentile hip width, 95th percentile buttock-popliteal length and 50th percentile elbow height sitting.* These specifications should satisfy ergonomic constraints. Use the anthropometric data reported by Gordon et al, 1989. When finished, click the 'Test Completed' button. Record the 'start' and 'stop' times. The time for this test is thirty minutes.

2. Second part:

Click the 'Start Test' button above, again.

Specify the dimensions for the backrest, seat and armrests of a seating system which a female, having *50th percentile body dimensions* will sit on for prolonged periods. These specifications should satisfy ergonomic constraints. Use the anthropometric data reported by Gordon et al, 1989. When finished, click the 'Test Completed' button. Record the 'start' and 'stop' times. The time for this test is thirty minutes.

Part II

In this part, you will simply use my ergonomic tool to repeat Test 1 & 2 above.

Assume that you are designing for the population with spinal cord injury.

Please note the time it took to determine the results.

Click on the following link to begin *Ergonomic Tool*

Thank you.

6.3 RESULTS

The results for the tests are below:

Table 6-1 Results

Test	Ergonomic Tool	Designer's current method
1	< 2 mins	Unable to complete test within 30 minutes
2	< 2 mins	Unable to complete test within 30 minutes

6.4 GENERALIZATION

In the following, the methodology presented in this thesis is generalized to the design of a pen.

1. Pen:- A pen is used for writing in order to communicate. For a pen that has a cover, a person is required to remove the cover before using the pen and also replace the cover afterward. These tasks are broken down into a sequence of subtasks.

   Sequence of subtasks for writing – grasp, lift, unscrew pen, lower, push, pull, lift, screw, lower. As can be seen, the first subtask simply involves touching the product (grasp) while other tasks are concerned with displacing the entire object or its components. It may also be assumed that the pen will be grasped for long periods of time.

   Product class – from table 4-2, the product code is 2111000000

   Ergonomic considerations – consider contact pressure, tissue distortion, moisture and temperature buildup, shear and friction in person-grasp surface interface. Consider static load due to prolonged grasping. Consider forceful exertions due to tactile force applied to displace entire product and its components. Provide clearance to grasp surface.

6.5 DESIGN AS A MULTIPLE OBJECVTIVE OPTIMIZATION PROBLEM

In arriving at a solution to a design problem, there are usually several objectives that need to be met. One objective may be to maximize safety and comfort while another could be to minimize cost. An optimum design problem must then be solved using these multi objectives and their associated constraints. This type of problem is known as a multiple objective (MO) optimization problem. In MO problems, the designer seeks values of the design variables, which optimize the objective functions simultaneously to produce a solution from a so-called Pareto optimal set from which the designer then makes a choice. It must be noted that in general, the optimal solutions obtained by individual optimization of the objectives may not be a feasible solution to the MO problem.

6.5.1 Constraint Relaxation

Ergonomic constraints are only one set of constraints that are considered in reaching a design solution. Other sets of constraints that may be taken into account are cost constraints, user-preference constraints, manufacturing constraints, etc. What this means is that in some situations, depending on the criticality of safety and comfort, ergonomic constraints may be relaxed, that is dropped, from the design problem.

Constraint relaxation is meant as a modification of a constraint network such that the network permits more solutions.[127] Relaxation may also be necessary when an original problem has no feasible solution or when the number of constraints associated with a design problem is numerous enough to be troublesome. In either case, some constraints may be relaxed, and the remainder of the problem solved.

6.5.2 Sensitivity Analysis

Sensitivity analysis ascertains how a design solution is affected by changes in the values of its input variables. This is important in checking the quality of a given model as well as a powerful tool for checking the robustness and reliability of its analysis. If a small change in an input parameter causes a relatively large change in a design solution, the latter is said to be sensitive to that parameter. This may mean that the parameter has to be determined very accurately or the problem, redesigned for low sensitivity.

7.0 CONCLUSION

In this thesis, a computer-aided ergonomic tool for conceptual design was constructed and tested on the design of a wheelchair seating system. Test results showed that the tool, which uses an expert system approach, was faster at generating ergonomic constraints for a design concept, than the current method. Existing computer-based tools are focused on design evaluation by which time it becomes more expensive to make design changes. The tool developed in this work therefore improves the CAD process since it fast tracks the design process by imposing ergonomic constraints early, thereby limiting design changes that otherwise would occur due to violation of ergonomic principles. This work is premier at applying the concept of group technology to classifying discrete product for ergonomic considerations.

Even though tissue integrity is a significant factor in the development of pressure ulcers, current seating systems standards do not take this factor into consideration. The CAD tool created in this work however, takes this factor into account. Manufacturers applying this tool to the design of seating systems and generally, all products a person will come in physical contact with, would make products with diminished risk of tissue breakdown.

The work conducted in this dissertation bridges a gap between the principles of ergonomic design theory and the practice of CAD across the broad spectrum of discrete manufactured products. This undertaking is a significant step towards improving the outcome of the CAD process since it enables input of ergonomics constraints at the onset of design. Thus, products are made safer and more comfortable to use. Hence, the sale of such products is enhanced, and post-market recalls are considerably minimized. Furthermore, since ergonomic constraints are imposed on a design early, design iterations are lessened, design cycle time shortened and the cost of product development, reduced. This should result in high quality goods delivered to the market at the right time and at the right price, thus enabling manufacturing companies meet or exceed their customer expectations, and hence stay ahead of the competition.

7.1 AREAS OF APPLICATION

This work accomplished in this dissertation has the potential to be applied to the following areas:

7.1.1 Service-Based e-Design and Realization of Discretely Manufactured Products

A service-based infrastructure for e-design and realization is an integration of product development tools over the Internet. This integration allows product development stakeholders VIZ end-users, designers, manufacturers, suppliers, sales personnel, etc, collaborate in product lifecycle management to shorten development time and cost. e-design involves conceptualizing, designing and realizing a product using tools that allow for interoperability of remote and heterogeneous systems, collaboration among remote supply chain and multidisciplinary enterprise product design team stakeholders, and virtual testing and validation of a product in a secure Internet based information infrastructure. Service to be provided by these tools could be for functional use by a person, an application program, or another service in the system, which is the core for integration of engineering tools.

The tool developed in this work has the capability of providing ergonomic service to a designer in an e-design environment. The tool will enable a designer determine ergonomic constraints pertaining to a product during the conceptual stage of design and utilizing these constraints, design alternatives can then be generated. Also since these ergonomic constraints are in computable form, they can easily be integrated into the CAD environment.

7.1.2 Application to Global Design

Design today, has become a global matter. Designers are thus required to take into consideration, the physical differences among the different world populations. Since this work has provided a general representation of ergonomic constraints in algebraic format, these constraints can thus be applied to the design of products for any world population. A designer is only required to apply the anthropometry of the target users and rules of thumb, in determining the bounds for ergonomic constraints.

7.2 AREAS OF FUTURE RESEARCH

7.2.1 Incorporation of Principles of Cognition

Human beings are made up of both mind and body. Therefore, taking cognitive as well as physical ergonomic constraints into account will produce products of higher quality. Hence, it is suggested that this work be extended to address the cognitive aspect of product users. Just like physical ergonomic principles, principles of cognitive need to be modeled and products classified for making cognitive considerations.

7.3 LIMITATIONS

The knowledgebase for the CAD tool developed in this dissertation is based on scientific research. As science advances, and new information becomes available, this tool will need to be updated otherwise the constraints it prescribes will become obsolete. One way to address this problem is to link the tool to a library system so that as new information becomes available, the tool can be automatically updated.

BIBILIOGRAPHY

[1] Lotter, B., Manufacturing Assembly Handbook. (Boston, MA: Butterworths, 1986).

[2] Kroemer K., Kroemer H, Kroemer-Elbert K., Ergonomics: How to Design for Ease and Efficiency, (New Jersey: Prentice Hall, 2001), p. 1.

[3] Bureau of Labor Statistics, retrieved June 15, 2004 from www.bls.gov.

[4] Nwaigwe A, Nnaji B., Taxonomy of Discretely Manufactured Products for Making Ergonomic Considerations, Proceedings of the 49th Annual Meeting of the Human Factors and Ergonomics Society, Orlando, FL (to be published).

[5] Bennett L., Kavner D., Lee B., Trainor F., "Shear versus Pressure as Causative Factors in Skin Blood Flow Occlusion", Archives of Physical Medicine and Rehabilitation, (1979), Vol. 60, pp. 309 – 314.

[6] Kosiak M., "Etiology and Pathology of Ischemic Ulcers", Archives of Physical Medicine and Rehabilitation, (1959), Vol. 40, pp. 62 – 69.

[7] Kernozek T. W. & Lewin J. E., "Seat Interface Pressures of Individuals with Paraplegia: Influence of Dynamic Wheelchair Locomotion Compared With Static Seated Measurements", Archives of Physical Medicine and Rehabilitation, (1998), Vol 79, 3, pp. 313 – 316.

[8] Park C. A., "Activity Positioning and Ischial Tuberosity Pressure: A Pilot Study", American Journal of Occupational Therapy, (1992), Vol. 46, 10, pp. 904 – 909.

[9] Clarke G., "The Problem of Pressure Ulcers and How to Treat Them", Journal of Therapy and Rehabilitation, (1997), Vol. 4, 11, pp. 589 – 595.

[10] Collins F., "Sitting: Pressure Ulcer Development", Nursing Standard, (2001), Vol. 15, 22, pp. 54 – 58.

[11] Sprigle S., "Prescribing Pressure Ulcer Treatment", retrieved on November 1, 2004, from REHAB Management, www.rehabpub.com/ltrehab/672000/5.asp, (June/July 2000), p. 1.

[12] Ebe, K., Griffin M. J., "Factors Affecting Static Seat Comfort", Ergonomics, (2001),Vol. 44, 10, pp. 901-921.

[13] Chow, W. W. and Odell, E. I., "Deformations and stresses in soft body tissues of a sitting person", Journal of Biomedical Engineering, (1978), Vol. 100, pp. 79–87.

[14] Chung K. C., "Tissue Contour and Interface Pressure on Wheelchair Cushions", Unpublished Dissertation, (1987), University of Michigan.

[15] Kadaba M. P., Ferguson-Pell M. W., Palmieri V., & Cochran G. V. D., "Ultrasound Mapping of the Buttock-Cushion Interface Contour", Archives of Physical Medicine and Rehabilitation, (1984), Vol. 65, pp. 467 – 469

[16] Swart M. E., "Physico-mechanical Aspects of Decubitus Prevention", International Journal of Rehabilitation Research, (1980), Vol. 8, 2, pp. 153 – 160.

[17] Bennet L., Kanner D., Lee B. K., & Trainor F. A., "Shear Vs Pressure as Causative Factors in Skin Blood Flow Occlusion", Archives of Physical Medicine and Rehabilitation, (1979), Vol. 60, pp.309 – 314

[18] Chow W. W., "Mechanical Properties of Gels and Other Materials with Respect to their Use in Pads Transmitting Forces to the Human Body", Unpublished dissertation (1974), University of Michigan.

[19] Sprigle S., Chung K.-C, & Brubaker C. E., "Factors Affecting Seat Contour Characteristics", Journal of Rehabilitation Research & Development, (1990), Vol. 27, 2, pp 127 – 134.

[20] Lange, M. L.. "Tilt in space versus recline-New trends in an old debate", Technology Special Interest Section quarterly, (June, 2000), *10,* 1-3.

[21] Brienze D. & Geyer M., "Support Surface Technology", retrieved on June 6, 2005 from http://www.wheelchairnet.org/WCN_WCU/SlideLectures/DAB/SuptSurfTech5.pdf

[22] Nicholson G. P., Scales J. T., Clarke R. P., & De-Calcina-Goff M. L. "A Method for Determining the Heat Transfer and Water Vapour Permeability of Patient Support Systems", Medical Engineering Physics, (1999), vol. 21, (10), pp. 701-712.

[23] Stewart S. F., Palmieri v., & Cochran G. V., "Wheelchair Cushion Effect on Skin Temperature, Heat Flux and Relative Humidity", Arch of Physical Medicine and Rehab, (1980), vol. 61 (5), pp. 229-233.

[24] Brienza D. M. & Geyer, M., "Support Surface Technology", retrieved from http://www.wheelchairnet.org/WCN_WCU/SlideLectures/DAB/SuptSurfTech5.pdf, on September 2, 2005, p. 42.

[25] Nicholson et al, Op Cit.

[26] Herman Miller Inc., "Body support in the Office: Sitting, Seating, and Low Back Pain", (2002), retrieved July 4, 2005 from, http://www.hermanmiller.com/hm/content/research_summaries/wp_Body_Support.pdf

[27] Macleod D., Op. Cit. p. 45.

[28] Attwood D., "Evaluation of Discomfort Experienced While Operating CADD Workstations", Proceeding of the 10th Annual Meeting of the Human Factors Society, (1986).

[29] Kroemer et al, Op Cit. p. 107.

[30] Bassey, E. J., "Physical Capabilities, Exercise and Aging", Reviews in Clinical Gerontology (1997) Vol 7, pp 289-297.

[31] Salvendy G., (ed.), Handbook of Human Factors and Ergonomics, (New York, NY: John Wiley & Sons), pp. 698 – 771.

[32] Schaub Kh. & Landau K., "A Computer-Aided Tool for Ergonomic Workplace Design and Preventive Health Care", Human Factors and Ergonomics in Manufacturing, (1997), Vol. 7, 4, pp. 269 – 307.

[33] Snook S. H. and Ciriello, V, M., "The Design of Manual Handling Tasks: revised tables of Maximum Acceptable Weights and Forces", Ergonomics, (1991), Vol. 34, pp. 1197 – 1213.

[34] Ciriello V. M., Snook S. H., and Hughes G. J., "Further Studies of Psychophysically Determined Maximum Acceptable Weights and Forces", Human Factors, (1993), Vol. 35, pp 175 – 186.

[35] Eastman Kodak Company, Ergonomic Design of People at Work (New York, NY: Van Nostrand Reinhold, 1983)

[36] Rosenberg D., "The Designers Guide to Portable Products", Proceedings of the Third National Symposium on Human Factors and Industrial Design in Consumer Products (1982), pp. 187 – 197.

[37] Kramer J. J. and Mequire P. G., "Consumer Product Portability as Related to Warranty Rulemaking", Proceedings of the Human Factors Society 21st Annual Meeting (177), pp. 287 – 291.

[38] Rosenberg D., Op Cit., pp. 187 – 197.

[39] Snook and Ciriello, "Maximum Weight and work Loads Acceptable to Female Workers", Journal of Occupational Medicine, Vol. 16, pp. 527 – 534.

[40] Davis K. G., Marras W. S., & Waters T. R., "Reduction of spinal loading through the use of handles", Ergonomics, (1998), Vol. 41, (8).

[41] Ndo S. A, No Y. O., Himaoka M. S., Iruta S. H., Attori Y. H., Ori F. H., Maeda T. I., & Akeuchi Y. T., "Strength and Perceived Exertion in Isometric and Dynamic Lifting with Three Different Hand Locations", Journal of Occupational Health, (2000), Vol 42. pp. 315 - 320.

[42] Gagnon M., Larrive A., & Desjardins P., "Strategies of load tilts and shoulders positioning in symmetrical lifting. A concomitant evaluation of the reference systems of axes", clinical Biomechanics, (2000), Vol 15, 7, pp. 478 – 488.

[43] Rosenberg D., Op Cit., pp. 187 – 197.

[44] NASA, Man Systems Integration Standards (Revison A), NASA-3000, (1989), (Houston, TX: L.B.J. Space Center).

[45] Goldsmith S., Designing for the Disabled, (1967), (New York: NY, McGraw-Hill).

[46] MIL-HDB 759, U.S.Army Missile Command, Human Factors Engineering Design for Army Material (Metric), (Philadelphia, PA: Naval Pubs. and Form Ltd., 1981).

[47] Woodson, Op. Cit.

[48] Cushman W. H. and Rosenberg D. J., Human Factors in Product Design, (New York, NY: Elsevier Science Publishers, 1991).

[49] International Organization for Standardization, http://www.iso.org/iso/en/ISOOnline.frontpage

[50] Webb Associates eds., Anthropometric Source book, Volume 2 (Springfield VA: Scientific and Technical information office, 1978) p. 1024.

[51] Webb Associates, Anthropometric Source Book, Vol. I, NASA 1024, National Aeronautics and Space Administration, Washington, DC, (1978).

[52] Roebuck, Kroemer K. H. E., and Thompson W. G., Engineering Anthropometry Methods, (NY: Wiley-Interscience 1975), p. 176.

[53] Dempster W., Space Requirements of the Seated OperatorWADC-TR-55-159, Aerospace Medical Research Lab, Dayton, Ohio, (1955).

[54] Goswami A., Ganguli S., and Chatterjee B., "Anthropometric Characteristics of Disabled and Normal Indian Men", Ergonomics, Vol. 30 No 5 (1987), pp. 817-823.

55 Open Ergonomics Ltd., retrieved on October 10, 2004, from http://www.openerg.com/psz.htm

56 MIL-STD 1472F, Department of Defense Design Criteria Standard. AMSAM-RD-SE-TD-ST, (Redstone Arsenal, AL: U.S. Army Aviation and Missile Command).

57 Roebuck et al, Op. Cit. p. 176.

58 Dempster, Op. Cit.

59 Dreyfuss H., The Measure of Man: Human Factors in design, The Whitney Library of Design, The Architectural Press, London, (1967).

60 Diffrient, Tilley, Bardagjy, Humanscale 1/2/3, MIT Press, Cambridge, Mass, (1978).

61 Diffrient, Tilley, Harman, Humanscale 4/5/6, MIT Press, Cambridge, Mass, (1981a)

62Panero J., Zelnik M., Human Dimension and Interior Space The Whitney Library of Design, The Architectural Press, London, (1979).

63 Woodson W.E., Human Factors Design Handbook, (1981),New York: NY, McGraw-Hill).

64 Tilley A., The Measure of Man and Woman, Henry Dreyfuss Associates, The Whitney Library of Design, The Architectural Press, London, (1995).

65 American National Standards Institute, "American National Standard for Wheelchairs (including Scooters)", Vol. 1, (1998).

66 Jastrzbska-Fraczek –Ing., Heiner Bubb rer. nat., "Software Design and Evaluation by Ergonomics Knowledge and Intelligent Design System (EKIDES)", Journal of PsychNology, Vol. 1, No. 4, (2003), pp. 378 – 390.

67 Woodcock A. and Galer Flyte M.D., Contemporary Ergonomics "ADECT - Automotive Designers Ergonomics Clarification Toolkit," (1997), 123-128.

68 Galer M. D., Harker S. D., Botley P., eds , "Methods and Tools in User Centered Design for Information Technology, "Human Factors Tools for Designers of Information Technology by Allison et al., " (Netherlands: Elsevier Science Pubs, 1992), pp. 13-42.

69 Green W. et al., "Evaluation Methods and Their Importance in Designing Interactive Artifacts by V. Popovic ," Chapter 2, p. 20.

70 Green W. et al., Op. Cit. "Safety in Consumer Product Design: Development of a Tool for Encouraging Ergonomics Evaluation in the Product Development Process by Norris B. and Wilson J.," Chapter 8, P. 79.

71 SAFEWORK - Human Modeling Technology, retrieved from http://www.safework.com/safework_pro/features.html

72 UGS - The PLM Company retrieved from http://www.ugs.com/products/efactory/jack/

73 SAMMIE CAD, retrieved from http://www.lboro.ac.uk/departments/cd/docs_dandt/research/ergonomics/sammie/samsum.htm

74 Green W., et al. , Op. Cit., "Designing for Usability; Input of Ergonomics Information at an Appropriate Form, in the Design Process by S. Porter S," Chapter 2, p. 15.

[75] Palil, D. M., Ergonomics Design: Artificial Intelligence and CAD for the Automobile Industry, Loughborough University, Unpublished dissertation.

[76] Green W. et al., "Ergonomics and Safety in Consumer Product Design: Development of a Tool for Encouraging Ergonomics Evaluation in the Product Development Process by B. Norris, and J. Wilson ," Chapter 8, p. 80.

[77] Cushman W. H. and Rosenberg D. J, Human Factors in Product Design Volume 14 (New York, NY: Elsevier Science Pubs. 1991), Chapter 14, p. 283.

[78] Cushman W. H. and Rosenberg D. J., Op. Cit. p. 286.

[79] Kroemer et al, Op Cit. p. 441.

[80] Kroemer et al, Op Cit. p. 533.

[81] Kroemer et al, Op Cit. p. 1.

[82] Chaffin D., Andersson G., Martin B., Occupational Biomechanics, (3rd edition; New York, NY: John Wiley & Sons, Inc., 1999), p. 10.

[83] MSN Encarta, retrived from http://encarta.msn.com/dictionary_/anthropology.html.

[84] Kroemer, et al, Op Cit., p.15.

[85] Roebuck et al, Op. Cit, p. 59.

[86] Caron et al, "Estimating the Center of Gravity of the Body on the Basis of the Centre of Pressure in Standing Posture - Technical note", J. Biomechanics, Vol. 30(11/12), (1977), pp. 1169-1171.

[87] LeVeau B., Williams and Lissner Biomechanics of Human Motion, 2nd edition; Philadelphia, PA Saunders, 1977).

[88] Lephart S., "Measuring the Inertia Properties of Cadaver Segments", J. Biomechanics, Vol.17, No. 7, (1984), pp. 537-543.

[89] Peyton A., "Determination of the Moment of Inertia of Limb Segments by a Simple Method", J. Biomechanics Vol. 19, No. 5, (1986), pp. 405-410.

[90] Van Cott H. P. and Kinkade R. G. (eds.) Human Engineering Guide to Equipment Design, "Engineering Anthropometry by H. T. E. Hertzberg," (Washington DC: US government printing office, 1972), pp. 467 – 584.

[91] HFES 300 Committee, Guidelines for Using Anthropometric Data in Product Design, (Human Factors and Ergonomics Society, 2004), p. 3.

[92] Chengalur S. N., Rodgers S. H., Bernard T. E, Kodak's Ergonomic Design for People at Work, (Hoboken, NJ: John Wiley & Sons Inc, 2004), p. 667.

[93] OSHA, retrived July 7, 2004
http://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=FEDERAL_REGISTER&p_id=16305#1c

[94] Frankel V. and Nordin M., Basic Biomechanics of the Skeletal System, by Lea and Febiger, (Philadelphia, PA, 1980).

[95] OSHA, retrieved July 3, 2004 from
http://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=FEDERAL_REGISTER&p_id=16305

[96] Silverstein B, Welp E, Nelson N, Kalat J., "Claims Incidence of Work-related Disorders of the Upper Extremities: Washington State, 1987 to 1995" American Journal of Public Health 88, (1998), pp. 1827-33.

[97] OSHA, retrieved July 3, 2004 from http://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=FEDERAL_REGISTER&p_id=16305

[98] Macleod D., The Rules of Work: A Practical Engineering Guide to Ergonomics, (New York, NY: Taylor & Francis, 2000), p.54.

[99] Merck, retrieved October 9, 2004 from http://www.merck.com/mrkshared/mmanual/section10/chapter122/122a.jsp

[100] Merck, retrieved July 11, 2004 from http://www.merck.com/mrkshared/mm_geriatrics/sec15/ch124.jsp.

[101] Wilson J. R., "Pressure and Procedures for the Design of Safer Consumer Products", Applied Ergonomics, (1983) Vol. 14 pp. 109-116.

[102] Chapanis A. "National and Cultural Variables in Ergonomics", Ergonomics, Vol. 17, pp. 153 – 175.

[103] HFES 300 Committee, Op. Cit, p.29.

[104] RESNA, retrieved on October 23, 2004 from http://www.resna.org/ProfResources/Publications/PubDesc/WheelchairStandards.php

[105] O'Reilly XML.com, retrieved October 23, 2004 from http://www.xml.com/pub/a/98/10/guide1.html#AEN58

[106] O'Reilly XML.com, retrieved October 24, 2004 from http://www.xml.com/pub/a/98/10/guide2.html

[107] Nwaigwe A, Nnaji B., Taxonomy of Discretely Manufactured Products for Making Ergonomic Considerations, Proceedings of the 49th Annual Meeting of the Human Factors and Ergonomics Society, Orlando, FL, (Sept. 2005).

[108] Burbridge, J., The Introduction of group technology, (NY:Halsted Press and John Wiley, 1975).

[109] Kroemer et al, Op Cit. p. 434

[110] Kroemer et al, Op Cit. p. 107.

[111] Bassey, E. J., "Physical Capabilities, Exercise and Aging", Reviews in Clinical Gerontology (1997) Vol 7, pp. 289-297.

[112] Salvendy G., (ed.), Handbook of Human Factors and Ergonomics, (New York, NY: John Wiley & Sons), pp. 698 – 771.

[113] Schaub Kh. & Landau K., "A Computer-Aided Tool for Ergonomic Workplace Design and Preventive Health Care", Human Factors and Ergonomics in Manufacturing, (1997), Vol. 7, 4, pp. 269 – 307.

[114] Rosenberg D., Op Cit., pp. 187 – 197.

[115] Rosenberg D., Op Cit., pp. 187 – 197.

[116] Eshback O. W. & Souders M. eds., Handbook of Engineering Fundamentals, "Mechanics of Rigid Bodies", by Rice J. M., (New York, NY: Wiley, 1975), pp. 429 – 485).

[117] Rosenberg D., "Human Factors for Portable Products", Proceedings of the Human Factors Society 25th Annual Meeting, (1981), Santa Monica, CA, pp.317 – 321.

[118] Rosenberg D., Op Cit., (1981), pp. 317 – 321.

[119] Chaffin et al, Op. Cit., pp. 364 – 374.

[120] Andersson G. B., Murphy R. W., Ortengren R. and Nachemson A., L., "The influence of Backrest Inclination and Lumbar Support on the Lumbar Lordosis in Sitting", Spine (1979), Vol. 4, pp. 52 - 58.

[121] Gordon, C., Churchill, T., Clauser, C., Bradmiller, B., McConville, J., Tebbets, L., and Walker, R. 1988 Anthropometric Survey of U.S. Army Personnel: Summary Statistics Interim Report (Technical report NATICK/TR-89-027), (Natick, MA: United States Army Natick Research, Development and Engineering Center, 1989).

[122] Rehab report # 21, "Our Mini-Guide to Cushions" (1999), Retrieved from http://www.wheelchairnet.org/WCN_ProdServ/Docs/TeamRehab/RR_99/Aug_99/9908art1.PDF

[123] Sprigle S., "The Match Game", Team Rehab Report, retrieved from http://www.wheelchairnet.org/WCN_ProdServ/Docs/TeamRehab/RR_92/9205art2.PDF

[124]Li Y., Aissaoui R., & Brienza D., "Determination of Generic Body-Seat Interface Shapes by Cluster Analysis", IEEE Trans on Rehab Engineering, (2000), vol. 8, (4), pp.481-489.

[125] Brienza D., Lin C., & Karg P., "A Method for Custom-Cuntoured Cushion Design Using Interface Pressure Measurements", IEEE Trans on Rehab Engineering, (1999), vol. 7, (1), pp. 99-108.

[126] Sprigle et al, Op. Cit.

[127] Walter, H. and Stephan, J., "Experimental Results in constraint Relaxation", retrieved on April 20, from http://www.cs.ucc.ie/~osullb/ercim2002/papers/hower.pdf