Ergonomic Simulation Revisited Using Parametric Virtual Humans in the Biomechanical Framework

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ÉCOLE POLYTECHNIQUE
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Dedication

To

Panasonic Electric Works Co., Ltd,

Dr. Junji Nomura,

(Former CTO, Panasonic Corporation)

(Late) Konosuke Matsushita

(Founder, Panasonic Corporation)

"It is my fundamental belief that a product should invoke

Kindness, charm, and grace and be delightful to the customer"

- **Konosuke Matsushita – 1942**

Résumé

L’approche CAO/FAO classique pour la conception ne montre pas les liens spatiaux essentiels entre l'utilisateur et le produit, ce qui est crucial pour une analyse de conception intuitive. Comme la population vieillit et le marché des appareils ménagers stagne, des principes de conception universelle utilisant des mondes virtuels deviennent plus importants pour répondre aux problèmes ergonomiques de populations hétérogènes. Ces problèmes sont de plus en plus difficiles à contrôler de manière adéquate avec des sujets du monde réel.
La représentation numérique de l'humain est un domaine récent qui fait le lien entre la conception assistée par ordinateur, l’ingénierie des facteurs humains et l'ergonomie appliquée. Les formes les plus avancées de cette technologie sont utilisées par de nombreux chercheurs pour des applications pratiques, incluant l'analyse ergonomique. Cependant, un état de l’art de cette technologie n'a jamais été conçu pour la phase de design conceptuel d'un cycle de développement de produits. Les raisons sont que la plupart des techniques classiques de représentation numérique de l'humain souffrent d’un manque d’interaction en temps réel, demandent une intervention considérable de l’usager, et ont des possibilités de contrôle inefficientes et des techniques de validation qui ne sont pas adéquates. Ceci contribue à ralentir les circuits de production. On peut encore noter que la réponse aux besoins de la population vieillissante croissante fait cruellement défaut dans de nombreuses sociétés à travers le monde.
L'objectif de cette thèse est d'introduire un cadre complet pour la simulation ergonomique au stade de la conception d'un cycle de développement de produit basé sur des humains virtuels paramétrés. Le travail s’appuie sur le cadre de la cinématique inverse avec priorités tout en prenant en compte les connaissances biomécaniques. En utilisant des commandes intuitives, les ingénieurs de conception peuvent saisir un modèle simple de CAO, entrer les variables et les facteurs humains dans le système. Le moteur d'évaluation va engendrer la simulation nécessaire en temps réel en utilisant une base de données anthropométriques, une base de données des caractéristiques physiques et une architecture de cinématique inverse avec priorités. Les principales composantes de l'ensemble du système sont décrites et les résultats sont présentés avec des applications telles que la conception de cuisines, de lavabos et de baignoires. En introduisant un algorithme d’estimation quantitative du vieillissement pour des modèles numériques anthropométriques de l'humain, les produits peuvent être conçus dès le départ pour répondre aux besoins ergonomiques de l'utilisateur plutôt que d’être à la merci des préjugés et des hypothèses du concepteur. On peut aussi noter qu’en créant un outil qui peut être utilisé de manière intuitive par des non-spécialistes dans un environnement dynamique et en temps réel, les designers peuvent se passer des spécialistes pour tester leurs idées et commencer à utiliser efficacement les données sur les populations afin de découvrir de nouveaux designs qui peuvent être utilisés plus facilement par plus de personnes. Les résultats ont été validés avec de vraies personnes montrant les implications pratiques de l'ensemble du système en tant qu’outil de conception ergonomique pour la phase de conception d'un cycle de développement de produit.

Mots-clés : humain virtuel, anthropométrie, modèle de vieillissement, conception universelle, conception ergonomique

Abstract

The conventional CAD/CAM approach to design does not show the essential spatial relationships between user and product that are crucial for intuitive design analysis. As populations age and the home appliance market stagnates, Universal Design principles implemented with computerized virtual worlds become more important for meeting the ergonomic problems of heterogeneous populations that are increasingly difficult to adequately test with real-world subjects.

Digital Human Modelling (DHM) is an emerging area that bridges computer-aided engineering design, human factors engineering and applied ergonomics. The most advanced forms of this technology are being used by many researchers for practical applications, including ergonomic analysis. However, a state of the art model of this technology has never been conceived for the conceptual design stage of a product development cycle as most conventional DHM techniques lack real time interaction, require considerable user intervention, and have inefficient control facilities and non-adequate validation techniques, all contributing to slow production pipelines. They have also not addressed the needs of the growing ageing population in many societies across the globe.

The focus of this dissertation is to introduce a complete framework for ergonomic simulation at the conceptual design stage of a product development cycle based on parametric virtual humans in a prioritized inverse kinematics framework while taking biomechanical knowledge in to account. Using an intuitive control facility, design engineers can input a simple CAD model, design variables and human factors in to the system. The evaluation engine generates the required simulation in real-time by making use of an Anthropometric Database, Physical Characteristic Database and Prioritized Inverse Kinematics architecture. The key components of the total system are described and the results are demonstrated with a few applications such as kitchen, wash-basin and bath-tub. By introducing a quantitative estimation of ageing algorithm for anthropometric digital human models, products can be designed from the start to suit the ergonomic needs of the user rather than the biases and assumptions of the designer. Also, by creating a tool that can be used intuitively by non-specialists in a dynamic, real-time environment, designers can stop relying on specialists to test the safety of their ideas and start to effectively use data about populations to discover designs that can be used more easily by more people. Results have been validated with real human subjects indicating the practical implication of the total system as an ergonomic design tool for the conceptual design stage of a product development cycle.

Keywords: digital human, anthropometry, ageing model, Universal Design, Ergonomic design

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I must say that the list is incomplete. *I thank one and all for their blessings and support throughout my life.*

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Section A

Introduction / State of the Art and Thesis Formulation

Chapter 1

Introduction

1.1 Background

Over the course of our lives, many of us will experience home environments that no longer help, but rather hinder our activities. Whether temporary or permanent, gradual or sudden, we find that stairs, tubs, or kitchens become hard or impossible to use safely. Some of these problems arise from disabilities. Disabilities come in a wide variety of forms and often in combination. Some are acquired through accidents or disease while others are congenital. They range from minor difficulties to the total inability to perform a task and can occur at any time in life. Indeed, as Ronald L. Mace makes clear, many of them inevitable: "*we all become disabled as we age and lose ability, whether we want to admit it or not. It is negative in our society to say "I am disabled" or "I am old". We tend to discount people who are less than what we popularly consider to be "normal". To be "normal" is to be perfect, capable, competent, and independent. Unfortunately, designers in our society also mistakenly assume that everyone fits this definition of "normal". This just is not the case*."

All our senses can be affected and often a decrease in function in areas such as touches and can manifest in the inability to grasp an object without crushing it or to find a doorknob in the dark. Our cognitive abilities or "the act or process of knowing both awareness and judgment" may be affected, creating a myriad of functional disabilities. Cognitive disabilities can affect all the senses, movement, balance, information processing, and speech in many combinations.

Such problems can have significant implications for carrying out our daily activities around the home. The problems and their implications need not prevent people from enjoying life and independent living, however. Basic home modifications and well-designed products can facilitate independent living and privacy. They can save time, promote ease of use, and offer convenience.

Universal design is an approach to design that considers how products, building features and other elements can be used to the greatest possible extent by everyone. While accessible or adaptable design requirements are specified by codes or standards for only some buildings and are aimed at benefiting only some people, the universal design concept targets people of all ages, sizes and abilities and is applied to all buildings.

Living spaces and household goods have long been designed for use by a single "average" physical type – young, fit, male, and adult. The fact is that only some of us fit that description and even then, only for a limited time. Whether young, old, or disabled, most people differ from the model used to design the products they use. "Designing all products, buildings, and exterior spaces to be usable by all people to the greatest extent possible" – the concept of universal design is becoming more and more important as populations age.

Given the relative maturity of technologies employed in home appliances, creating distinctive products is a challenge. Manufacturers have been seeking to increase added value by improving product performance with diverse functionalities, but have achieved little success in developing products with significant advantages over the competition. Recently, competing in markets has been like betting on a horse race with the winners coming struggling against 5-to-1 or 10-to-1 odds: that is not that the winning horse is five or ten times faster than the others, in quality he may only win by a nose, but rather that the rewards are five or ten times greater! In such an environment, all a company needs is a winning edge and in many markets, accommodating the human factor *is* that edge. Put briefly, human-centered product design has become ever more important in order to survive in a global market.

1.2 Context of the Work

Today, engineering design is in the midst of a paradigm shift, from fitting the human to the system to fitting the system to the human. Rapid growth of an ageing population and a stagnant home appliance market has prompted designers to pay much more attention to barrier-free and universal designs (UD), that's why designers have been focusing to incorporate anthropometry and age factors into their product designs. .

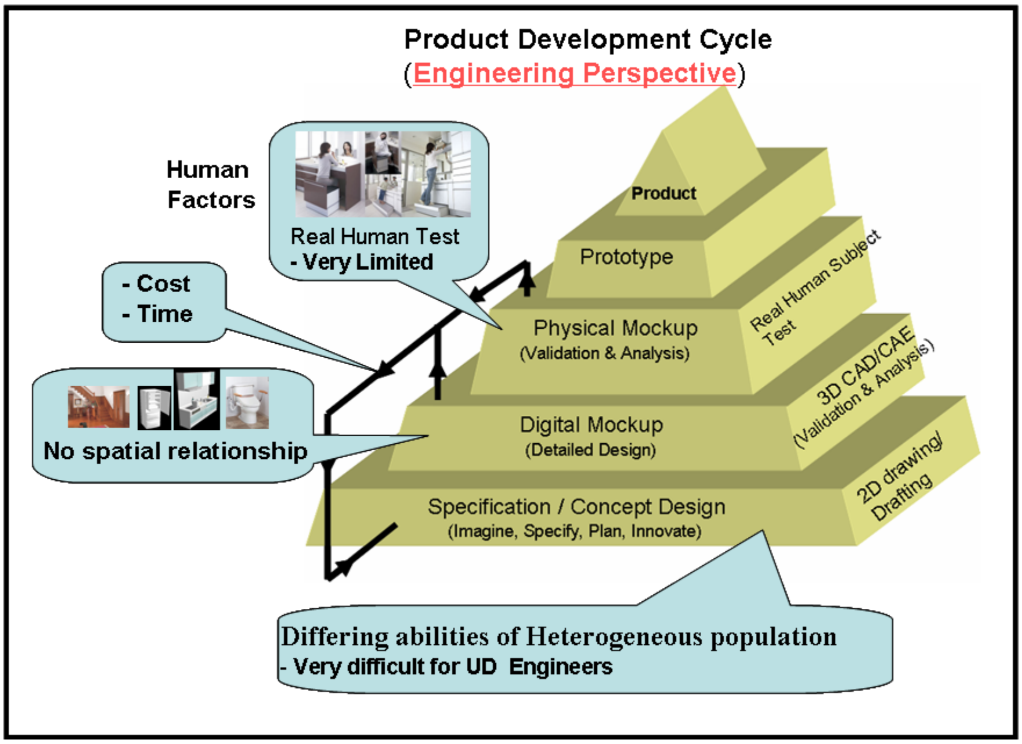


Figure 1: Product Development Cycle from an Engineering Perspective

The traditional way to realize and identify an ergonomic problem is to visualize it through the evaluation of physical product mock-ups with actual human subjects. However, there are significant limitations to this approach in terms of cost, time, and the diversity of test subjects. While an alternative might be to perform such ergonomic evaluations within a "digital world", the conventional CAD/CAM approach does not show the essential spatial relationships between user and product that are crucial for intuitive design analysis. The state of the art of product development cycle and conventional step-by-step approach from an engineering perspective is shown in Figure 1.

Lowest layer of conceptual design stage makes use of 2-D drawing and drafting. From the view point of UD Engineers, designing a product that could “be used more easily by more people” is not a trivial task. It is very difficult to infer the differing abilities of a heterogeneous population at the concept level leading to a bad ergonomic design.

Both the shrinking time frames for product design, manufacture and consumer demands for more convenience, comfort and safety, point to the need for ergonomic design tools with specific population attributes that can merge with 3D graphics renderings of proposed work environment. Digital Human Modeling (DHM) is rapidly emerging as an enabling technology and a unique line of research that promises to profoundly change how products and systems are designed, how ergonomic analyses are performed, and how human disorders or impairments are assessed. An overview of the current developments in digital human modeling can be found in [BUB 99], presenting different approaches ranging from simply integrating force data for specific tasks at defined postures to detailed simulation of individual muscles in musculoskeletal models like the Anybody modeling system [RAM 03]. In research and development, commercial human models are already being used. These models are now mainly restricted to anthropometric issues. The two human models often used, JACK and RAMSIS have been mostly applied in the automobile industry.

Despite successful use as a digital mock-up, a state of the art model of this technology has never been conceived for the conceptual design stage of a product development cycle as most conventional DHM techniques lack real time interaction, require considerable user intervention, and have inefficient control facilities and non-adequate validation techniques, all contributing to slow production pipelines. They have also not addressed the needs of the growing ageing population in many societies across the globe. These expensive packages also have poor CAD systems and user interfaces.

Panasonic’s UD concept seeks to develop products which will help to create inclusive societies in which people of all kinds can enjoy high amenity life styles. *The objective of revisiting ergonomic simulation is to address the abovementioned bottlenecks through Panasonic’s ideology*.

1.3 Goal and contributions

Our goal is to introduce a novel approach to replace the traditional 2-D drawing and drafting with populated 3-D world in order to incorporate human factors at the conceptual design stage.

The investigation is formulated on two aspects in the context of computer-aided ergonomics or a user-centred design process both as an applied technology and as a fundamental research area. As an applied technology, this research would be a means to create, manipulate, and control *heterogeneous population representations and human-machine system scenes on computers* for interactive ergonomics and design problem solving in the context of *universal design applications, at the conceptual* *design stage of product development cycle*. As a fundamental research area, this work should refer to the development of *empirically validated ageing models and algorithms* that are sufficient enough to predict human behaviour in response to minimal command input and allow *real-time computer graphics visualization.*

With an intuitive control facility, design engineers would be able to input a simple CAD model and design variables and human factors into the system. An evaluation engine would generate the required simulation in real-time at the conceptual design stage using of user-models that are representative of the heterogeneous population being served. The system would be an efficient tool to help designers more quickly and easily identify ergonomic flaws thus helping society better facilitates the differing abilities of an ageing heterogeneous population through universal design.

1.4 Potential Applications of the Proposed System

The human aspect of design is crucial and arguably has two aspects, one being the role that the designer has in producing products and systems that relate to the users themselves. The other is the way that the designer can be supported to be more creative and innovative. The provision of innovative support tools within the engineering design process is essential for the effective delivery of high quality products and systems

Our proposed system would be a broad platform as an ergonomic evaluation engine, by which a non-specialist user can experiment with and manipulate anthropometric data intuitively in real time. Proposed tool caters to the need of the design engineers by expanding the range of option available to them during the conceptualization stage of the design. A design engineer would utilize the tool for feasibility testing of the design, even in the nascent stage of its formulation, due to the real time application of the tool, as it comprises of extended range of human factors almost reaching to the limit of a real human subject. Apart from this, the tool promises to realize the potential of universal design which aims to making facilities, information resources, and services accessible to the heterogeneous population along with its typical attributes.

A complementary direction of the present research is to create a decision-making tool that enables customers to more easily evaluate existing products by feeding their specific requirement as input into the system, and as a promotional tool to demonstrate the effectiveness of new designs.

1.5 Outline of the Thesis

This dissertation is organized by dividing it in to **Five Sections** alphabetically A, B, C, D and E.

Section A introduces the thesis with state of the art and thesis formulation. It consists of Chapter 1, being introduction of the research work and its context. Chapter 2 gives an overview of the state of the art of ergonomic design and digital human modeling techniques in the context of applied ergonomics. The chapter discusses the potential limitations of the available systems to approach common design problems especially in the context of universal design applications. An introduction of the hypothesis which aims to address the limitations of the existing state of the art and overview of the scientific approach to realize the hypothesis has been explained in the later part of the chapter.

Section B comprising of the chapter 3 and 4, where the former discusses the method of developing parameterized virtual humans in the bio mechanical framework and latter deals with experimental analysis to verify the accuracy of the biomechanical model.

Section C explains the flexibility and strength estimation based on age. It consists of two chapters; chapter 5 and chapter 6 where the former introduces our strategy for strength estimation and the latter explaining the quantitative estimation of ageing algorithm.

Section D deals with the development of functionalities towards the realization of the total system as an Ergonomic Evaluation Engine. The section also includes postural control techniques with prioritized inverse kinematics architecture.

The dissertation concludes in **Section E** by mentioning possible future directions.

Chapter 2

State of the Art

Ergonomics is a branch of science drawing from physiology, engineering and psychology studies. It seeks to harmonize the functionality of tasks with the human requirements needed to perform them. Historically Ergonomics was another name for human factors. Today, Ergonomics commonly refers to designing work environments for maximizing safety and efficiency. Biometrics and anthropometrics play a key role in this use of the word ergonomics. Ergonomic design focuses on the compatibility of objects and environments with the human using them. The principles of ergonomic design can be applied to everyday objects and work spaces.

2.1 Ergonomic Design

The International Ergonomics Association [IEA 04] defines the discipline of ergonomics as: "*the scientific discipline concerned with the understandings of interactions among humans and other elements of a system, and the profession that applies theory, principles, data and methods to design in order to optimize human well-being and overall system performance. Ergonomists contribute to the design and evaluation of tasks, jobs, products, environments and systems in order to make them compatible with the needs, abilities and limitations of people.*" [SHA 91] state that the prime purpose of ergonomics is to study the situation of people at work and play, and thus be able to improve the whole situation for the people, and that ergonomics always remains user-centered and focused on users' wellbeing rather than on productivity, even though managers and designers sometimes need the argument of improved productivity or economy to employ ergonomic knowledge. In short the aim of ergonomics can be described as "fitting the system (or the product) to the user".

Among the basic disciplines contributing to ergonomics are psychology, cognitive science, physiology, biomechanics, applied physical anthropometry and industrial systems engineering [KRO 01]. The field of ergonomics is commonly divided in to the areas of ***physical ergonomics, cognitive ergonomics and organizational ergonomics*** [IAE 04]. The terms ergonomics, human factors, human factors engineering and human engineering are usually considered synonymous [PIC 00], [KRO 01], and the term ergonomist represent persons working in the area of ergonomics.

Usability is a term related to ergonomics. The international Standards Organization [ISO 98] defines usability as: "the extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use."

'Classic' research in the area of ergonomics typically deals with characteristics of the human body and mind, e.g. related to dimensions, limitations, capabilities or expectations. Compilations of detailed ergonomics information can be found in sources such as [SAN 93] and [KRO 01].

[SAG 03] make a distinction between design ergonomics and corrective ergonomics. They define design ergonomics as an approach where ergonomics starts in the initial design phases with a needs analysis and then is applied throughout the design process. This is in contrast with corrective ergonomics, which involves modifications to existing products or systems, often within very restricted limits, to overcome problems relating to safety, health, comfort and the efficiency of the human-product system. In this thesis, when the term ergonomics is used it relates to the definition of design ergonomics.

An important area within ergonomics is Anthropometry which is the science of measurement and the art of application that establishes the physical geometry, mass properties and strength capabilities of the human body [ROE 95]. Anthropometry belongs to the branch of physical ergonomics.

2.1.1 Product development & design process

These days, the development of products generally leads to complex design processes where a multifaceted approach is required to meet and exceed customer's expectations. The competition is tough and global, and it is fair to say that it is the customer's market, i.e. it is the customers who to a large degree set the rules for the companies to act within. The internet and globalization has made it easier for customers to get information about alternatives when looking for a product to buy, as well as to find the best offer for the desired product; this being core of the market economy. In addition to the complex design process where numerous, often conflicting requirements have to be treated and balanced, time pressure is also typically present.

One wide spread approach to support or enable this is integrated product development [AND 87], [AND 91] or Concurrent Engineering [CLA 97], where people are working in an integrated manner, in cross-functional teams, typically involving marketers, design engineers and production engineers, and where activities are performed more or less in parallel. Also extensive us of design methods and computer tools such as CAD, CAE, PDM (Product Data Management), PLM (Product Lifecycle Management), CAM (Computer Aided Manufacturing), VR (Virtual Reality) and simulation software is employed to shorten lead time and assist integrated work. The main objectives promoting the approach are reduced time to market, reduced costs and improved product quality.

There are numerous models, explanations and representations of design processes available in design literature, all aimed at describing or prescribing the complex process of design [CRO 00]. Typical design process models are those of [ARC 63], [FRE 85], [PAU 88], [HUB 92], [PUG 95], [ULR 03] and [ULL 03] and the general conclusion is that there are benefits from using structured design methods in modern product development, and it is suggested, at least initially, to uphold a 'keep-it-simple, keep-control' approach towards the methods, and a tolerance of adapting the methods according to the context within which they are applied.

2.1.2 Universal design

Universal Design (UD) is an approach that seeks to develop products, services and facilities for maximum user- friendliness by avoiding particularities of design so that they can be used readily by the widest range of people regardless of age, sex, race, shape or physical ability. The intent of universal design is to simplify life for everyone by making products, communications, and the built environment more usable by as many people as possible at little or no extra cost. Universal design benefits people of all ages and abilities.

Principles of UD

1. Equitable Use

The design should be useful and marketable to people with diverse abilities. Following guidelines have to be incorporated in the process of universal design to make it more equitably used across the population.

a. Provide the same means of use for all users: identical whenever possible; equivalent when not.

b. Avoid segregating or stigmatizing any user.

c. Provisions for privacy, security, and safety should be equally available to all users.

d. Make the design appealing to all users.

2. Flexibility in Use

To be a universal design, a design should accommodate a wide range of individual preferences and abilities, keeping following requirements as guidelines

a. Provide choice in methods of use.

b. Accommodate right- or left-handed access and use.

c. Facilitate the user's accuracy and precision.

d. Provide adaptability to the user's pace.

3. **Simple and Intuitive Use**

Use of the design should be easy to understand, regardless of the user's experience, knowledge, language skills, or current concentration level. In order to make the product simple and easy to use following condition should be incorporated in the design.

a. Elimination of unnecessary complexities.

b. Design should be consistent with user expectations and intuition.

c. Accommodation of a wide range of literacy and language skills.

d. Arrangement of information consistent with its importance.

e. Provision of effective prompting and feedback during and after task completion

4. **Perceptible Information**

The design communicates necessary information effectively to the user, regardless of ambient conditions or the user's sensory abilities. To facilitate perceptible information dynamically the design should be inclusive of following scenarios.

a. Use of different modes (pictorial, verbal, tactile) for redundant presentation of essential information.

b. Provision of adequate contrast between essential information and its surroundings.

c. Maximize "legibility" of essential information.

d. Differentiate elements in ways that can be described (i.e., make it easy to give instructions or directions).

e. Provide compatibility with a variety of techniques or devices used by people with sensory limitations.

5. **Tolerance for Error**
   The design should minimize hazards and the adverse consequences of accidental or unintended actions by taking following points in consideration.
   a. Arrange elements to minimize hazards and errors: most used elements, most accessible; hazardous elements eliminated, isolated, or shielded.
   b. Provide warnings of hazards and errors.
   c. Provide fail safe features.
   d. Discourage unconscious action in tasks that require vigilance.

6. **Low Physical Effort**
   The universal design consideration must ensure that the design can be used efficiently and comfortably and with a minimum of fatigue by adopting following guidelines.
   a. Allow user to maintain a neutral body position.
   b. Use reasonable operating forces.
   c. Minimize repetitive actions.
   d. Minimize sustained physical effort.

7. **Size and Space for Approach and Use**
   Appropriate size and space should be provided for approach, reach, manipulation, and use regardless of user's body size, posture, or mobility. Provision of unhindered accessibility for the user should comprise of the following conditions

   a. Provide a clear line of sight to important elements for any seated or standing user.
   b. Make reach to all components comfortable for any seated or standing user.
   c. Accommodate variations in hand and grip size.
   d. Provide adequate space for the use of assistive devices or personal assistance.

2.1.3 Computer aided design

A wide spread tool for today’s designers is a CAD system. Typical advantages of such tools are the ability to model, view and easily modify the product in a three dimensional virtual environment. CAD also enables simulation of issues like assembly, manufacturing, packaging, appearance and mechanical properties. CAD also supports rapid prototyping techniques. An obvious advantage would be if ergonomics could be, albeit only roughly, simulated and evaluated in a virtual environment, preferably within the same CAD system used for designing the product. This would support product designer’s consideration of ergonomics, together with many other aspects, in product design. Even though such tools, often called human simulation tools or human modeling systems, have existed since late 1960s [POR 93], and their functionality is constantly improving, they are rarely used by ‘traditional’ design engineers in their day-to-day work, but rather by experts, e.g. specialized ergonomists or simulation engineers. Reasons for the limited use may be high investment costs or skills required for employing human simulation tools properly in product development. The perception may be that the tools give too restricted benefits in relation to the effort of buying, learning and using them. Another reason may be tradition among design engineers of mainly focusing on the physical product, rather than on circumstances associated with the wider human-product interaction.

2.2 Digital Human Modeling for computer-aided Ergonomics

While human modeling has always been at the forefront of ergonomic research, it is being propelled at an unprecedented tempo in the digital age by the advancement of computer technology. Digital human modeling is rapidly emerging both as an applied technology and a unique line of research, with the promise to profoundly change how products or systems are designed, how ergonomics analyses are performed, how disorders or impairments are assessed, and how therapies or surgeries are conducted. This section discusses the state of the art of digital human modeling both as an applied technology and as a fundamental research area, in the context of computer-aided ergonomics.

2.2.1 History of Digital Human Modeling for Ergonomic Design

The use of digital human models to improve certain ergonomic attributes in a proposed design is not a new concept. Various types of digital human models have been around for over 35 years. Pilots reach requirement assessments of people of varied anthropometry [RYA 69], seated digital human model by [CHA 70]. Evans and Chaffin [EVA 85] described how work place and task information could be integrated with a wire mesh 3D avatar to perform ergonomic assessments. During the same time, in the late 1970s JACK was being created at the University of Pennsylvania and was commercially available by late 1980s as a tool to allow a user to easily manipulate simple movements and object-grasping tasks [BAD 93]. The main field of application of mannequin JACK is animation and visualization in vehicle design and architecture. Also by the late 1980s evaluation of pilot and maintenance tasks was done by U.S Air force using the derivatives of the earlier Boeing model, entitled COMBIMAN and CREWCHIEF [MCD 90]. During the 1980s, the computer man model SAFEWORK was developed at the Ecole Polytechnique in Montreal. It covers three modules: anthropometry, movement, and analysis. SAFEWORK was conceived for workplace designs in factory planning as well as in product designing. It is being used by Chrysler, Boeing, and various universities and academies. The newest development in North America is the project Virtual Soldier, initiated and supported partly by the U.S Army TACOM project and by Caterpillar Inc. project Digital Human Modeling for Safety and Serviceability. It is called Santos [ABD 06], and promises to be the next generation of virtual humans. It is an anatomically correct human model with more than 100 degrees of freedom. The ongoing project is to develop a system in which an avatar’s motion is controlled by a variety of human performance measures.

The European developments basically followed the same directions as their American colleagues. The development of computer man model SAMMIE (System for Aiding Man-Machine Interaction Evaluation) was started in 1967. This system consisted of 3D polygons. The 5^{th}, 50^{th}, and 95^{th} percentile male model was available [CAS 90]. In the early 1980s, an extensive development of computer models started in many different institutions throughout continental Europe. 3D man model, ERGOMAN was created in France in 1984, allowing analysis of moving areas for the arms and legs. Besides the analysis of car interiors, further applications existed in the aerospace industry and the railway industry [HIC 85]. Another development was done by INERTS, in cooperation with French automotive industry, which led to the non-commercially available man model Man 3D, especially used to calculate gripping areas in cars. Recently, more often used commercial packages are RAMSIS and ANYBODY. RAMSIS was developed to aid in the design of ergonomic interior of vehicles. After an extensive evaluation phase in 1995, the system was commercially offered worldwide. ANYBODY is relatively a new development [RAS 03] aiming an accurate modeling of the muscles and their connection to the skeleton. Attempts also have been done for safety evaluation and a couple of commercial products are MADYMO-3D and PAM-CRASH.

Altogether, more than 150 man models exist worldwide that have been developed for specialized industries like automobile, clothing, shoes and military use including work space design and product design. Unfortunately, their acceptance and use have not been rapidly assimilated in to organizations to improve the ergonomic design of most of the hardware and software systems used today. This is despite the fact that the benefits when using such a technology have been well acknowledged over the last decade in books by [BAD 93], [PEA 93], and [CHA 01].

As a fundamental research area, there has been tremendous improvement in digital human modeling both in body shape modeling and motion modeling. The digital human creation of varying level of detail using computer graphics is a well-documented topic [KAL 98], [AUB 00], [BAD 02], [HYE 04], [RAM 03]. Towards ergonomic design, an overview of the current developments in digital human modeling can be found in [BUB 09], presenting different approaches ranging from simply integrating force data for specific tasks at defined postures to detailed simulation of individual muscles in musculoskeletal models like the anybody modeling system [RAM 03]. The CAESAR data set [CAE] has been a tremendous boon to the study of the space of contemporary body shape. There has been a notable effort to use the CAESAR data to anthropometrically and continuously scale body shapes by fitting skeleton in to the shapes based on surface land marks [ALL 03]. Subsequently, the SCAPE project extended these methods to include deformable bodies and motion data obtained from non-CAESAR subjects [ANG 05].

In the case of human motion prediction models, there has been four basic computational procedures and they are forward or direct kinematics, Inverse kinematics, forward or direct dynamics, or inverse dynamics. Models have been categorized in to four classes by Chafin for computer aided ergonomics and they are

1) Static models without musculature – Models in this class use static optimization and inverse kinematics to solve a discrete posture determination problem.

2) Static models with musculature – These have been were built mainly for the purpose of estimating muscle forces and joint loading. Such models apply static optimization and inverse dynamics to a static posture or a series of discrete postures in a movement.

3) Dynamic models with musculature – The static models with musculature evolved into dynamic models, incorporating neuro-muscular-skeletal forward dynamics and dynamics optimization, for rendering simulated human movement.

4) A dynamic model without musculature- By excluding the musculature, computational efficiency is expected.

Various motion simulation methods have been developed during the last few decades; yet at this time, the human motion simulation technology, as a whole, does not seem to have reached the level of sophistication necessary to support its wide use in design practice. Human motion and posture simulation aims to accurately predict natural human motion trajectories or postures for given input simulation scenarios [CHA 05], [HIS 94], [JUN 95]. An input simulation scenario is typically specified as a brief description of the task and the performer. The output is a whole-body motion trajectory (typically, a set of joint angle-time trajectories) or a posture (a set of joint angles) that corresponds to the input scenario. The output motion trajectory is computed by a mathematical model, algorithm, or empirically developed equations. It is then visualized via anthropometrically correct, articulated digital human figures within a computer-aided design environment.

Chaffin [CHA 09] gives an overview of the technical challenges to improve the DHM simulation for computer-aided ergonomic design and they are

1) Human model accuracy

2) Coupling of DHM avatar with CAD

3) Integrating Avatars and human performance models and

4) Task planning techniques.

Similarly, Badler [BAD 09] mentions the tools for future human factor analysis as the following (Excerpt from his paper)

"*Tools for human factors analysis should include*

- *Methods for obtaining baseline data on human shape, joint articulation, and joint limits*
- *Methods for acquiring empirical motion data from people in order to create predictive models for novel situations*
- *Methods for setting up and running analyses efficiently and effectively, with readily modified populations or work space modifications*
- *Methods for digitally simulating the normal and exceptional tasks a human may be called on to perform, including sensing and reacting to others and the environment*

No single human factors tool or system has this complete set of functionalities."

2.3 Need for the Revisit of Ergonomic Simulation

2.3.1 State of the Art – Summary

A large body of literature has grown up around the field of ergonomics and digital human modeling and numerous studies have demonstrated its effectiveness in improving the quality of life of individuals as well as the efficiency of workers. Nevertheless, its widespread adoption continues to be hampered by the costs inherent in implementing universal design concepts, the ease of use for tools that facilitate its design, and the accuracy of human models used to validate its use. Even as the considerable gains in computational power and 3D modeling tools become more widely available, the pursuit of realistic visual modeling of humans used in mass media has not provided affordable tools for effectively modeling the mechanical behavior of humans necessary for real-world design applications.

Despite successful use as a digital mock-up, a state of the art model of the digital human modelling technology, comprising of solution for the problems of heterogeneous population has never been conceived for the conceptual design stage of a product development cycle. As of today, most conventional DHM techniques lack real time interaction of the designer with the initial design model, require considerable user intervention, and have inefficient control facilities and non-adequate validation techniques, all contributing to slow production pipelines. They have also not addressed the needs of the growing ageing population in many societies across the globe. These expensive packages also have poor CAD systems and user interfaces.

2.3.2 Panasonic's Universal Design Policy

Panasonic’s Universal design concept seeks to develop products which will help to create inclusive societies in which people of all kinds can enjoy high amenity life styles. Designing a product that could “be used more easily by more people” is not an easy task. It is very difficult to estimate a design from all people’s view point. UD engineers have to presume the different abilities of various people. Panasonic’s universal design policy espouses following six basic elements.

a. Making operations easily understandable.
b. Using easy-to-understand indications and expressions
c. Providing users with stress-free postures and movements
d. Users' movements and space
e. Users' safety and sense of security
f. Operating environment

Orientation of this research is towards addressing the limitations of the existing state of the art which provides scope for a tool that eliminates the bottlenecks in designing process and also cater to differing demographic attributes of present and coming generations. Our approach integrates the vision of Panasonic’s UD policy with the existing bottlenecks faced by designers, along with an eye for the anticipated challenges emerging from future dynamics.

2.4 Formulation of the thesis

2.4.1 Introduction

To incorporate human factors at the conceptual design stage we intend to replace the traditional 2d drawing/drafting with 3d world, consisting of heterogeneous population of user models [Figure 2.1]. It may seem obvious that the most important two key factors we have to keep in mind are 1) Real-time simulation and 2) Direct on-line interaction of end-users with the system; such that even a non-specialist should be able to use the system through traditional interaction devices like the mouse. Using an intuitive control facility, design engineers should be able to input a simple CAD model, design variables and human factors in to the system.

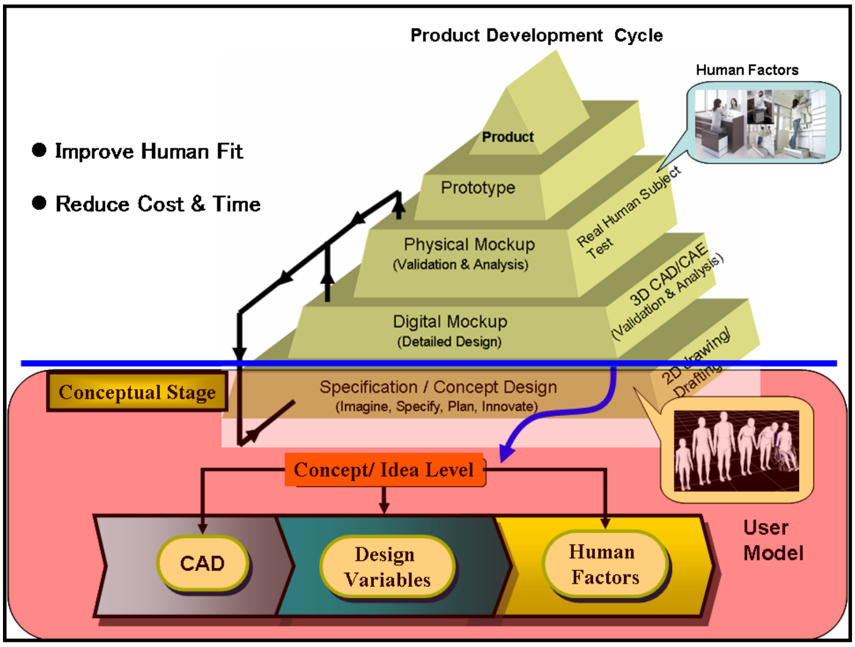


Figure 2.1: Revisit of Product Development Cycle by introducing Human Factors at the conceptual design stage

2.4.2 Problem Statement

Our investigation would focus on developing an Ergonomic Evaluation Engine for the conceptual design stage as shown in the figure 2.2. In other words, the work will include the development and integration of the following basic building blocks:

- Functions to create the user model of any body size, shape and strength along with real time motion/posture control.
- Functions to create 3D product models (using primitive geometries) from 2D images/drawing
- Interface functions between user model and product model
- Assessment functions for ergonomic evaluation

- Viewer and interface functions.

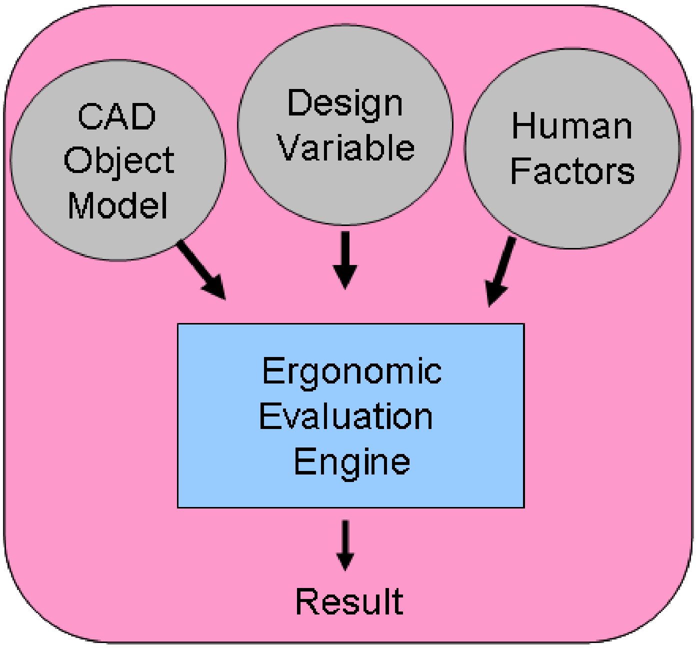


Figure 2.2: Abstract view of the total system as an Evaluation Engine

To replace traditional 2D drawing/drafting with a 3D world populated with user models, the key factors to keep in mind include:

- **Real-Time Simulation**

The user model should have sufficient level of sophistication to realistically represent the human body's usual range of movement as well as model its usual postures and movements realistically. At the same time, computational algorithms must remain time-efficient, allowing real-time rendering. Here the test for physical realism is based less on appearance than on its validity for biomechanical or ergonomic analysis.

- **Direct on-line interaction of end-users with the system**

Assuming that design-engineers are not ergonomic professionals, the total system should be designed such that even a non-specialist can use it intuitively and interactively through traditional interaction devices like the mouse.

- **Coupling of User Models with CAD**

Coupling adequate human models with a designable virtual environment is still challenging but necessary to quickly determine how different environmental variables affect ergonomic indices of interest for different tasks.

- **Task Planning**

Providing high level task descriptors as input to the system is very important to allow users who are not human factors specialists to effectively simulate complex human-machine interactions while maintaining consistent and accurate results.

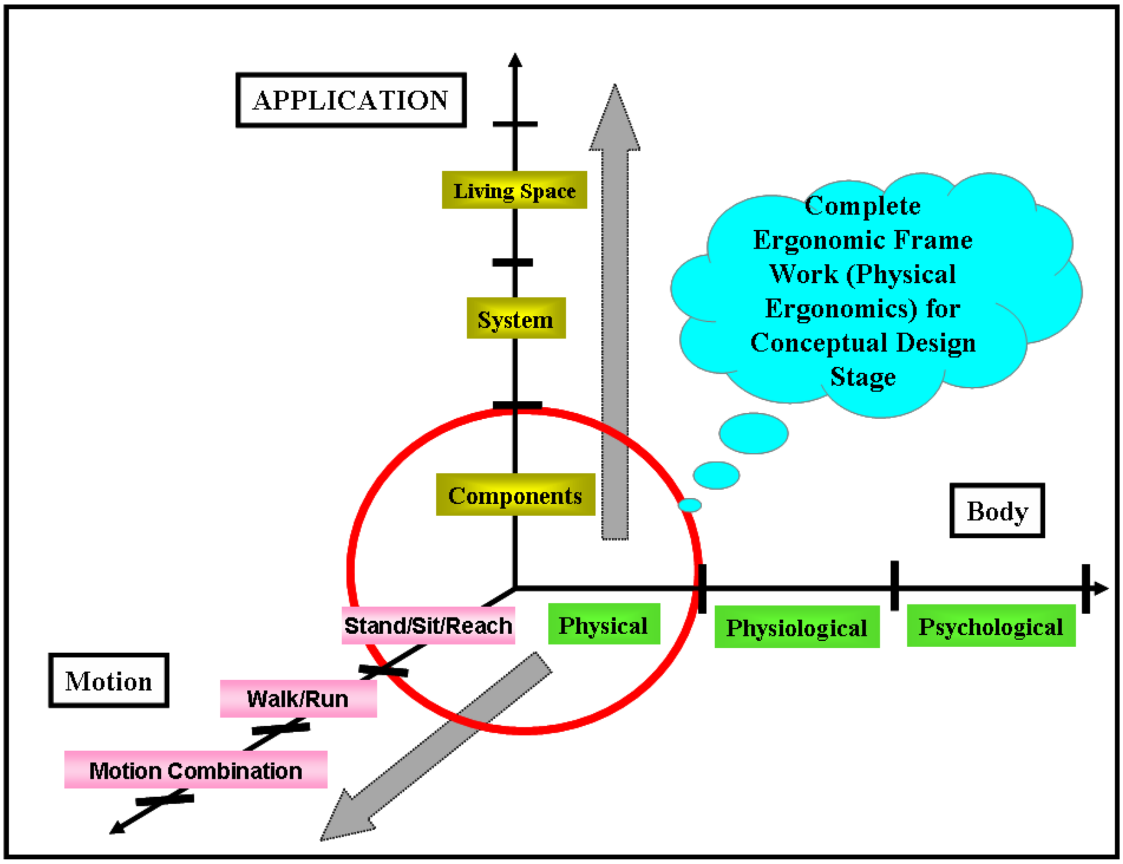


Figure 2.3: Focus of our Research

The abstract overview of the strategy is shown in Figure 2.3, with three axes showing Body, Motion and Application respectively. Application is categorized into three levels: components, system and Living space (e.g. household items in the home such as a kitchen could be considered as a system while a shelf or sink in the kitchen could be considered as components). Human model is broadly divided into *body* and *motion* and each category is subdivided into three levels as shown in the figure. Our research focus is the shown inside the red circle where the body model is limited to physical aspects, motion is restricted to joint level posture manipulation (especially with the basic stand/sit/reach postures), and application is limited to components. At the conceptual stage, we are more interested in evaluating the strength and flexibility at different ages with interactive, intuitive real time postural control. *Effect of ageing on postural variation of virtual humans is beyond the scope of this dissertation.*

2.4.3 Total system architecture and the scientific approach

Abstract overview of the system architecture can be shown as depicted in figure 2.4. User interface layer integrates the user with the simulation system, where user can be a designer or a consumer. For a designer the system will act as an ergonomic design tool while for a consumer it functions as a decision making tool. System interface layer connects the simulated virtual human with the virtual world.

User interface layer provides for a graphical interface for the interaction of the user with the simulation system. Interface layer for the user consists of generation of user model, CAD object model, camera view orientations and creation of functions for scenario assessment, to name a few.

Core of the simulation system consists of modules for creating body, strength and motion control of virtual humans.

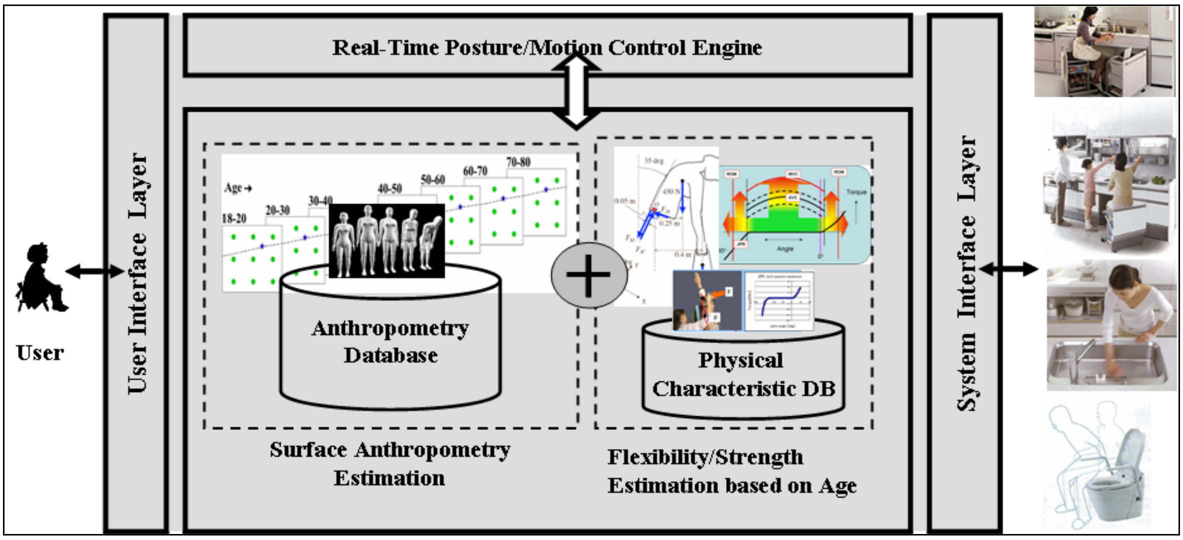


Figure 2.4: Overview of the total system architecture

Our approach to the problem is formulated on two aspects in the context of computer-aided ergonomics or a user-centred design process both as an applied technology and as a fundamental research area. As an applied technology, this simulation would be a means to create, manipulate, and control *heterogeneous population representations and human-machine system scenes on computers* for interactive ergonomics and design problem solving in the context of *universal design applications, at the conceptual design stage of product development cycle*. As a fundamental research area, this simulation should refer to the development of *empirically validated ageing models and algorithms* that are sufficient enough to predict human behaviour in response to minimal command input and allow *real-time computer graphics visualization*.

As a fundamental research area, we investigate the development of empirically validated digital human ageing models, in the context of *physical ergonomics*. The research includes:

- Surface anthropometry estimation using available database
- Biomechanical encapsulation & validating the accuracy of the biomechanical model
- Estimation of flexibility and strength for different ages.
- Development of ageing algorithm for anthropometric models
- Encapsulation of postural control techniques (age factor is not included for the posture) for the whole population for reach, step up and object manipulation tasks

As an applied technology, our investigation would focus on developing an Ergonomic Evaluation Engine for the conceptual design stage by coupling the scientific results from the fundamental research area with the components of the proposed work environment. In other words, the work will include the development and integration of the following basic building blocks:

- Integration of the digital human model (user model) with the conceptual design stage
- Functions to create 3D product models (using primitive geometries) from 2D images/drawing
- Interface functions between user model and product model
- Assessment functions for ergonomic evaluation
- Viewer and interface functions and the integration of the total system as an Ergonomic Evaluation Engine

2.5 Original Contribution

The focus of this dissertation is to introduce a complete framework for ergonomic simulation at the conceptual design stage of a product development cycle based on parametric virtual humans in a prioritized inverse kinematics framework while taking biomechanical knowledge into account. Using an intuitive control facility, design engineers can input a simple CAD model, design variables and human factors in to the system. The evaluation engine generates the required simulation in real-time by making use of an Anthropometric Database, Physical Characteristic Database and Prioritized Inverse Kinematics architecture. The project aims to make *two original contributions as well as a number of sub-contributions:*

Contribution 1:

Includes an ageing algorithm for anthropometric digital human models

Articulated biomechanical models have been reported by many researchers for ergonomic applications. Chaffin gives comprehensive analysis techniques in his book [CHA 99] and Ayoub shows the mathematical approach in their book [AYO 89]. For ergonomic applications, an articulated biomechanical model will not be sufficient to analyze the human factors without a method to validate whether joint torques generated by a digital human for a particular posture is permissible or within affordable limits. These methods should include validation techniques for a single digital human as well as for the ageing population. Chaffin [CHA 99] has compiled Joint Moment – Strength Mean prediction equations for an average human, but those equations are not enough when we deal with whole population. In this regard, we intend to introduce a quantitative approach to strength estimation for a whole population by making use of a physical characteristic database of actual human subjects. Our research will be complementary to those prior investigations but distinguished from them by adding an ageing module as the key factor. Our approach is empirical and our models derive directly from data.

Contribution 2:

Provides a broad platform by which a non-specialist user can experiment with and manipulate anthropometric data intuitively in real-time

Traditionally, articulated biomechanical models are the province of specialists. This fact alone inherently limits the usefulness of such tools to testing large, expensive, pre-existing designs despite their great potential as design tools. This limitation is compounded by the large amount of time that such tools require to return useful feedback. By providing intuitive manipulation and creation of the models, non-specialists can begin applying their own branches of expertise to put these tools to new purposes altogether. Rather than testing a few existing designs, all types of new designs can be created and experimented with. By providing instantaneous feedback that responds dynamically to a user's input, the tool ceases to operate as a means of testing designs and becomes a tool for discovering new and revolutionary designs that might not have even been imagined otherwise. As such, the effect of the contribution is not merely quantitatively superior, but qualitatively novel and innovative.

Sub-contributions:

- Coupling of DHM with CAD (Generic method/techniques for task planning and setting up the design variables.)
- Replacing of 2D drawing/drafting with 3D world
- Real-time Intuitive interactive control for the whole population for reach, step up and object manipulation tasks
- Estimation of Affordable Voluntary Contraction (AVC) for different age groups
- Total system as a generic ergonomic evaluation engine for the conceptual design stage
- A decision making tool that enables customers to more easily evaluate existing products

2.6 Schematic organization of the forthcoming sections

In order to achieve the intuitive, real time and dynamic features and to create a broader platform of an evaluation tool, for universal design applications, over which even a non-specialist can manipulate and customize a user-model according to his choice we are constructing a digital human model.

In the first stage a surface anthropometric model of the digital human is created based on the particular age and associated physical features of that age group by incorporating the biomechanical knowledge in the design. The second stage examines the physical strength estimation of the real human biomechanically, keeping the factor of aging in perspective and integrating it with the articulated link structure of the model. The third stage focuses on the real time motion and postural control of virtual humans using the principles of Inverse kinematics. Evolution of total system as an ergonomic evaluation engine is achieved with the integration of CAD object model, design variables and human factors into the developed system.

Section B

Parameterized Virtual Humans in the Biomechanical Framework

Chapter 3

Surface Anthropometry Estimation and Biomechanical Encapsulation

An anthropometric model is characterized by the exterior skin model that gives it a realistic appearance as well as by the interior skeleton model. The task of this interior model is to represent all posture and motion functions of the human body using as few joints as possible. However, due to recent improvements in computing capabilities, this restriction has become less significant, favoring a more realistic representation of the functionality of the skeleton. The visual aspect of human modeling draws heavily on the field of computer graphics, which in turn includes computer science, solid modeling, and advances in the movie and 3D gaming industries. Given the physical ergonomic application of the project, our virtual human models will be limited to biomechanical models consisting of a hierarchy of rigid segments connected by joints at a basic level.

3.1 Surface anthropometry estimation using Geometry Database

To create surface anthropometry we make use of an anthropometric database of Japanese people. The database has been published by the Research Institute of Human Engineering for Quality of Life (HQL) [BSD 97].

3.1.1 Origin of the statistics

The database contains body size information details of a sample of population randomly chosen across the regions. Research Institute of Human Engineering for Quality Life (HQL), established in 1991 for the research of human factors, measured the Japanese body size twice as national project.
This database has basic information of 34000 subjects gathered from north to south of Japan and their statistically processed data. Data collection period is from 1992 to 1994 and the age of the subjects varied from 7 to 90 years (Please refer to Table 1 of Appendix A-1 for the population sample based on age.) Each datum consists of 178 measurement items. These measurements were decided based on a questionnaire investigation of measured places that companies needed for their human oriented development. (Please refer to Appendix A -2 for the details of the 178 measurements.). The HQL database is available at [HQL 92].

Figure 3.1 graphically depicts the demographic distribution of the subjects (both genders) grouped according to their respective age layers. Graph systematically represents the number of subjects of both genders falling in different age groups.

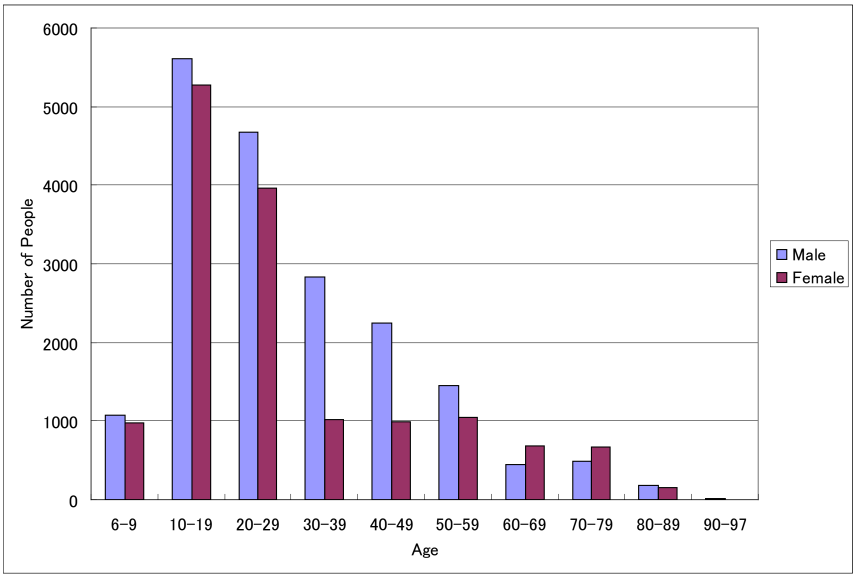


Figure3.1: Demographically distributed Customized database with age group of 10 years, showing number of samples at each age layer

Traditional methods were used to measure each man in specific posture. Appendix A contains the measurement details along with the posture, sample distribution based on age and measurement items. Probable errors in the measurement are caused by machine operators, subject trembling and measurement person, but the measurement was very massive so that the error effects were very negligible according to HQL [BSD 97]. During measurement along with traditional instruments 3-D measurement devices were also used. Figure 3.2 shows the traditional devices for the measurement of face and hand and for body.

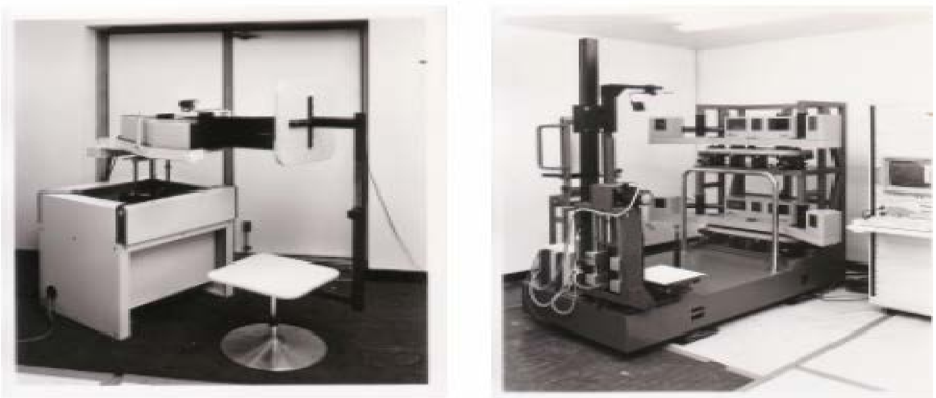


Figure 3.2: 3-Dimensional measurement device for face and hand and for body.

3.1.2 Skeleton and Surface Model Estimation Technique

To create surface anthropometry, population sample drawn from database has been arranged into age groups as shown in Figure 3.3. Parameters associated with these age groups such as height, waist, weight are catalogued into 3-dimensional model. Population sample database divided into 3-D age layer having x, y, z axis representing a specific parameter such as height, waist and weight. Please refer Appendix A-3 for height, waist and weight distribution.

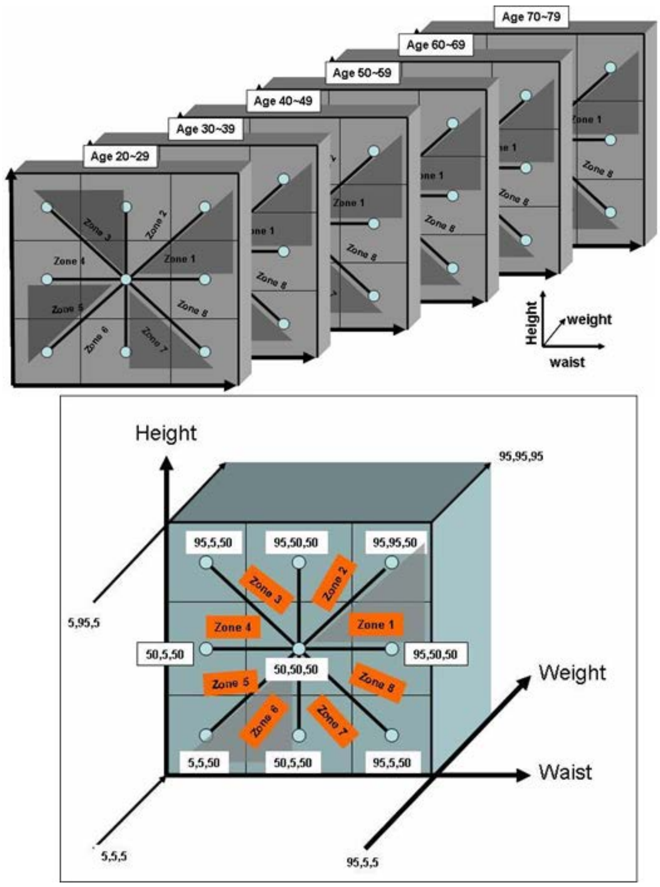


Figure 3.3: 3-D representation of parameters such as height, weight and waist for each age layer.

A zoomed version of an age layer is shown in the bottom part of the Figure 3.3, in which the layer is further divided into 9 patterns (8 zones) on a percentile basis, so that all measurements are distributed in nine groups of percentiles, (5,5), (5,50), (5,95), (50,5), (50,50), (50,95), (95,5), (95,50), and (95,95), for each particular layer. Each layer is 3-dimensionally marked with axes for height, waist and weight parameters and is classified into 8 zones.

Keeping one parameter constant (e.g. weight) a 2-D space is created for zone identification in which a certain population having physical measurement of each body part is stored in an n-dimensional space, where n is the number of measurements. Each zone is located according to two remaining parameters which act as the identifier for the location of the user on the 2-D map.

For creation of the 3-D surface anthropometry of the user we further extract his each body segment's measurement by making use of the existing database. After zone identification the concerned user information extraction is done. User information is embedded in a 2-D space. Each physical measurement value is assigned a corresponding 2-D space. Actual values obtained from the existing database have been kept as reference points. For a random physical measurement value extraction these reference points would act as beacon and a relative measurement value is calculated using the vector sum method. For all vital physical measurements (each body segment) their corresponding 2-D space (length, breadth) is addressed. The skeleton model of the virtual human is constructed according to the physical measurements of the body parts thus obtained. Figure 3.4 shows the abstract overview of the model creation method.

As a first step towards 3D model generation, the body model has been simplified into 18 parts and each part has been linked by a hierarchically articulated structure. We use H-Anim Standard as the basis of the articulated structure, which is a series of interdependent local coordinate systems strategically positioned at locations within the 3D model to suggest shoulders, elbows, knees, and so on.

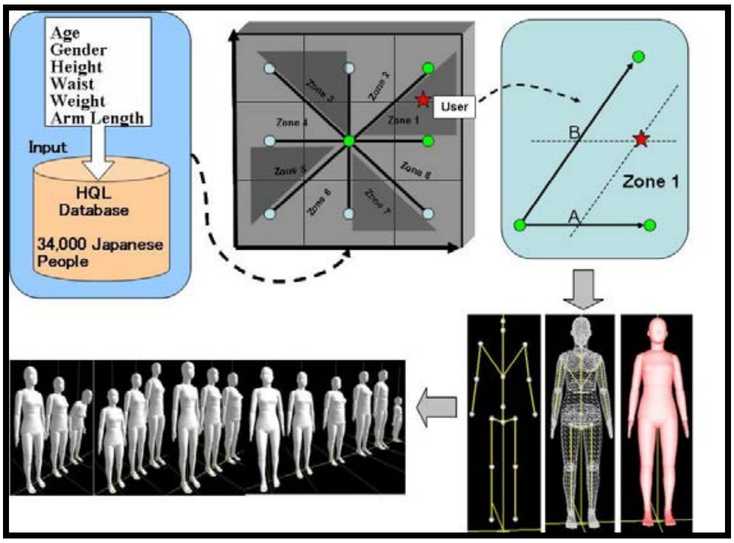


Figure 3.4: Method of creating User-model from the database, with an example of user value placed at Zone 1

The dataflow and the step by step approach for estimating characteristics of the user model that is shown in Figure 3.4 (with a user model in zone 1 as an example) is briefly described below with a flowchart as shown in Figure 3.5

Based on the height and waist of the user, assuming that the user- zone is identified as Zone 1 (marked * as user in Figure 3.4). His/her measurements are extrapolated using the measurements available at zone 1 and they are base model data (50, 50), model data at (95, 50) and (95, 95). Based on the estimated measures, surface anthropometry for each part has been re-calculated and merged with modified skeleton model. An approximate aged representation of the user has then be extrapolated using the zone correction function by making use of the relative position of the user model at the present layer and mapping the values to corresponding zone in the aged layer (adjacent layer) on a percentile basis.

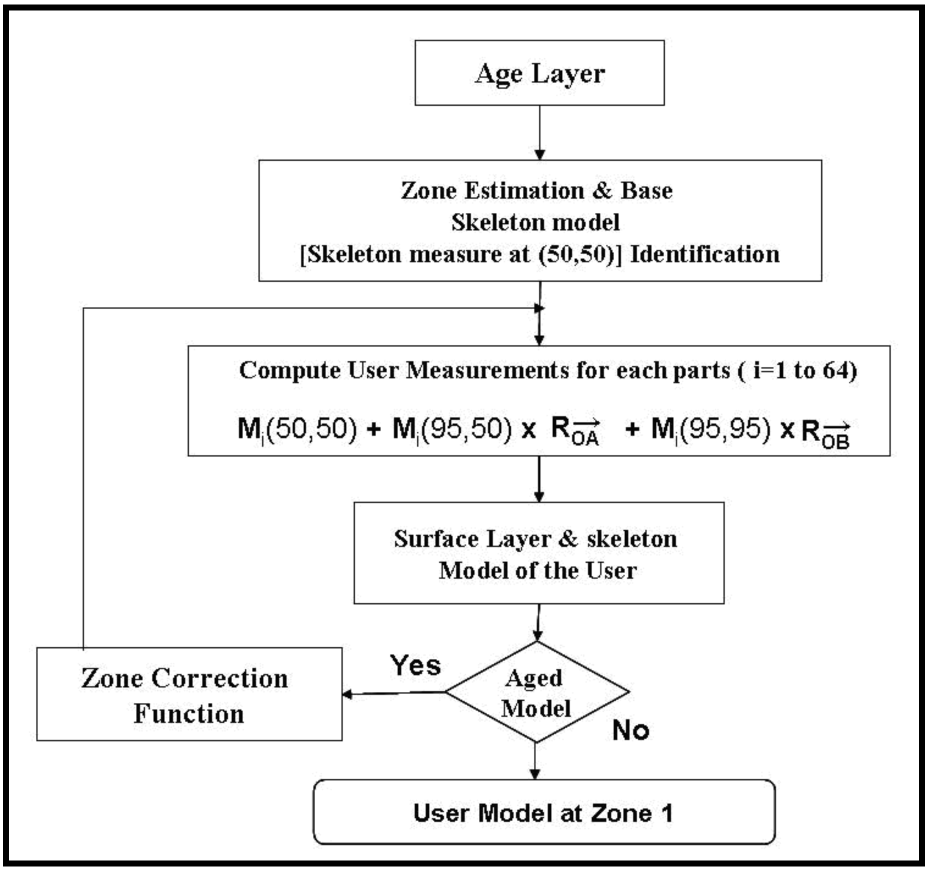


Figure 3.5: Overview of the data-flow to generate a User-model that is placed in Zone 1

Using this customized database, our system can create empirically validated digital humans of any size, height, age, waist, and weight and arm length. Our approach is similar to the work reported by [DOU 98], whose focus was on the face anthropometry.

3.2 Encapsulation of Biomechanical Knowledge

Considering body as a system of levers, torque estimation is performed at each joint (i.e. lever) using biomechanical approach. Contini and Drills (1966) defines biomechanics as '*the science which investigates the effect of internal and external forces on human and animal bodies in motion and at "rest"* '.

Biomechanics, in turn, can be divided into general and applied biomechanics. While general biomechanics deals with the fundamental laws and rules governing organic bodies at rest or in motion, occupational biomechanics which is a subdivision of applied biomechanics, involves the principles of biomechanics towards work in improving in everyday activities, especially dealing with human disorders and performance limitations which exists at present in a variety of manual task in the industry [AYO 89].

3.2.1 Articulated Link Structure

The whole body model is upgraded to the biomechanical model that has an articulated link structure with joint models.

The location where two bony parts meet is called joint or *articulation*. Human joints are usually split into three categories by anatomists according to their range of motion: inmovable, slightly movable, or freely movable. Alternatively, joints are classified according to their structure. At any rate, both classifications are very similar due to the close relationship between the structure of a joint and the range of motion it allows. In computer graphics, Joints are classified according to the type of motion they allow.

Hinge Joints: A hinge joint is a monoaxial joint. The rotation takes place about an axis perpendicular to the long axis of the bones involved. This transverse axis allows flexion/extension motion, usually with a considerable extent. The direction which the distal bone takes in this motion is seldom in the same plane as that of the axis of the proximal bone; there is usually a certain amount of deviation from the straight line during flexion. The interphalangeal joints and the elbow joint between the humerus and the ulna are examples of hinge joints. The knee and ankle joints are less typical, as they allow a slight degree of rotation or of side-to-sidemovement in certain positions of the limb.

Pivot Joints: A pivot joint is also a monoaxial joint but, in this form, the rotation takes place
about a longitudinal axis. It supports angular movement around the long axis of a bone, allowing one bone to rotate in the ring of another bone. Both articulations of the radius with the ulna (proximal and distal) are pivot joints.

Ball-and-socket Joints: A ball-and-socket joint allows rotational movement in all planes. A
bone with a rounded end (ball) fits in a cuplike cavity (socket) of another bone, hence the name ball-and-socket. The range of motion depends to a large extent on the depth of the socket; a shallower socket increases the range of possible motions, but the stability of the joint suffers. The shoulder is a shallow ball-and-socket joint. The hip is another ball-and-socket joint.

Ellipsoidal Joints: An ellipsoidal joint is a modified ball-and-socket joint, where an ovalshaped knob on one bone is received into an elliptical cavity on another bone. This design allows all movements allowed by ball-and-socket joints, except axial rotation. The wrist joint is an example of this form of articulation.

Figure 3.6 is a pictorial representation of virtual human model showing joint types and the degrees of freedom associated with them. The purpose of the joint model is to define limits on the joint coordinates.

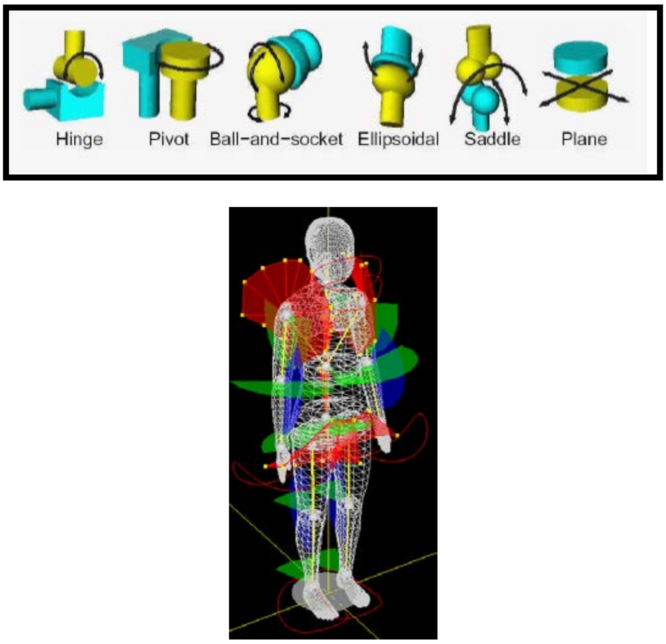


Figure 3.6 Joint types and the example of developed virtual human model

3.2.2 Body Mass Distribution

To describe the mass distribution of digital humans, we use the so called augmented body (an imaginary rigid body supported by, and implicitly associated with, each joint in the current state of the system). The mass distribution of each part of the body is different for gender as well as young and aged. Our models are based on the distribution provided by [MIC 92][HID 96] as shown in Table 3.1 and an example of the distribution as an augmented body in the case of the human having a weight of 60 kg can be represented as shown in Figure 3.7

	young				old			
	male		female		male		female	
	mass(%)	center of mass(%)	mass(%)	center of mass(%)	mass(%)	center of mass(%)	mass(%)	center of mass(%)
head	6.9	82.1	7.5	75.9	9.1	86.9	8.8	83.8
trunk	48.9	49.3	45.7	50.6	49.7	49.8	49.3	51.5
upper arm	2.7	52.9	2.6	52.3	2.5	54.9	2.5	56.9
forearm	1.6	41.5	1.5	42.3	1.7	42.7	1.6	42.3
hand	0.6	89.1	0.6	90.8	0.8	82	0.6	76.3
upper leg	11	47.5	12.3	45.8	9.2	48.1	9.8	47.4
lower leg	5.1	40.6	5.3	41	4.7	42.3	4.8	42.4
foot	1.1	59.5	1.1	59.4	1.7	58.1	1.5	59.1
chest	30.2	42.8	26.7	43.8	28.8	40.9	26	41.7
torso	18.7	60.9	19	59.7	20.9	60.5	23.4	58.7

Table 3.1 Body Mass Distribution young and old for both genders

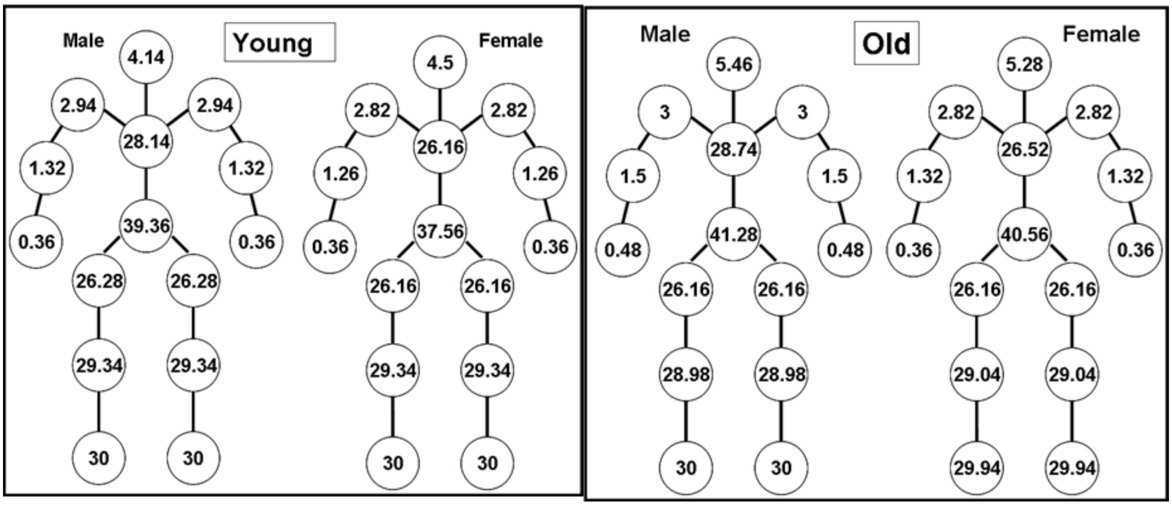


Figure 3.7: Body mass distributions, using augmented body concept for both young and old, with an example weight of 60 kg

3.2.3 Torque Estimation

To compute the torque generated by the articulated system a free body diagram of the system is conceived. The fundamental law of Statics states that, whenever a posture is in equilibrium position, both the sum of the external forces and the sum of their moments, expressed at the global center of mass, have to vanish. Consider the case of a hand holding the weight. The load acting at the hand produces a torque at the elbow as does the weight of the forearm and hand. The involved muscle's contractile activity then produces the necessary torque to counterbalance these torques.

Mass distribution of various body segments is accumulated at joints in a hierarchical manner. The distribution of accumulated weight over the joints is shown with the help of augmented body concept, which is the imaginary rigid body supported by the joints in the current state of the system.

Torque generated by any articulated joint is based on the accumulated weight experienced at that particular joint. Figure 3.8 shows the pictorial representation of torque exerted at each joint by conceiving each joint is as the simple lever and the body as the system of levers. In the static equilibrium situation, the sum of the torques about the point of rotation must be zero, according to the Newton's law. With changing posture of the body, the centre of gravity shifts. To maintain the balance, moment expressed at the overall centre of mass of the body must me equal to zero.

Σ moments (M) = 0; Σ Forces (Fx or Fy) = 0.

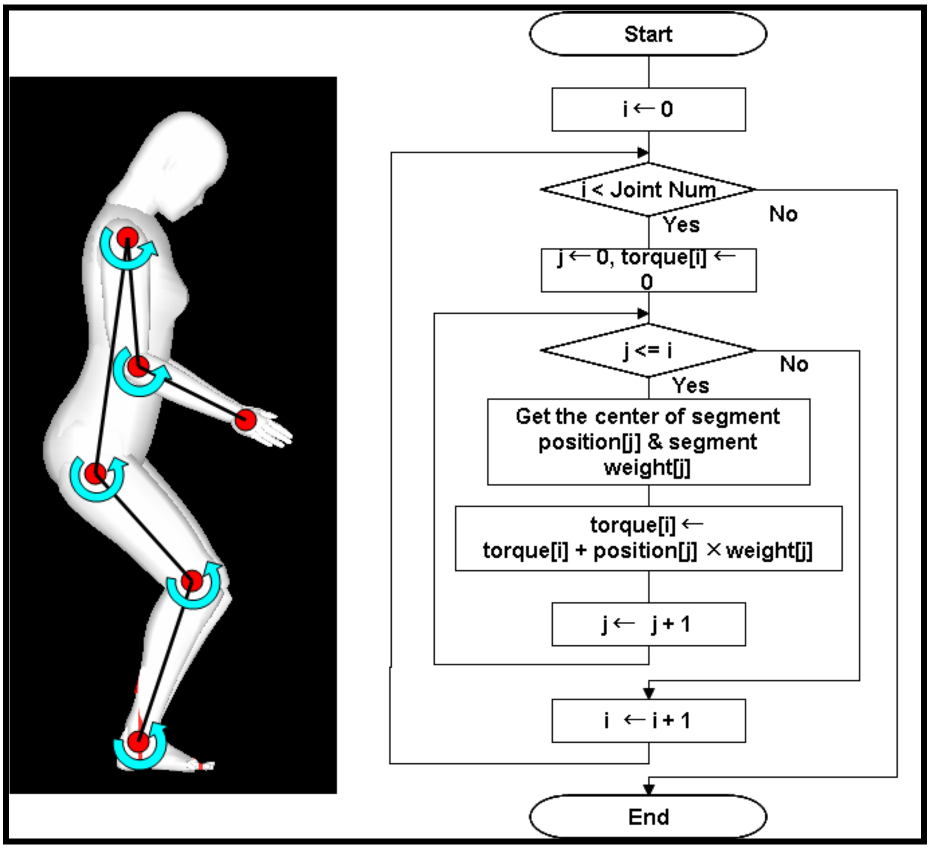


Figure 3.8 Torque Estimation techniques based on the biomechanical approach

3.3 Conclusion

The chapter described the first stage of development of the digital human model i.e. surface anthropometry estimation based on age using Geometry Database. The anthropometric model can be understood as exterior skin model giving it realistic appearance and interior skeleton model representing all posture and motion functions of the human body while using as few joints as possible. Through incorporation of biomechanical knowledge this whole body model of the digital human is upgraded as an articulated link structure with joint models. Torque estimation for each joint of the model using free body diagram technique has been done.

Chapter 4

Experimental Analysis to Verify the Accuracy of the Biomechanical Model

4.1 Centre of gravity analysis and correction for the biomechanical model

The body balance is obtained by controlling the position of center of mass with a technique called inverse kinetics, which integrates the body mass distribution information for single or multiple supports.

To validate and correct the accuracy of the biomechanical model, specifically for the center of gravity location, weight distribution on the foot and the weight distribution while at the seated-posture, an experiment has been setup **with real human** subjects as described below.

Process: To estimate the pressure on the sheet for each pattern/posture using the pressure measuring sheet BIG-MAT (Nitta corporation).

4.1.1 Real- Human subjects:

Sample population of 6 people of both genders having age of 30, 50, 70 years are taken and three body posture, i.e. standing, sitting and step-up (one leg-stand straight) are monitored for mapping the location of center of gravity and the distribution of weight over the area covered of the sheet under the foot. The selected posture patterns are the following and the snapshot of the setup is shown in Figure 4.1

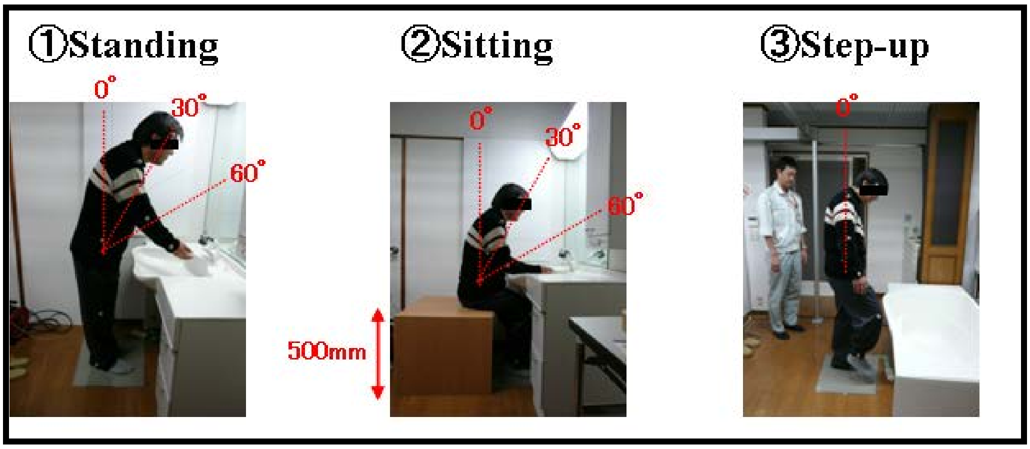


Figure 4.1 Experiment with real-human subjects for CG correction

4.1.2 Posture Patterns:

The Centre of Gravity (CG) and the pressure experienced over the entire foot, a real human is tested in different body postures. The posture patterns in our analysis were the following.

1) Standing (3 patterns with straight 0 degree, 30 and 60 degrees)

2) Sitting (3 patterns with straight 0 degree, 30 and 60 degrees)

Chair – height: 500 mm, 600 mm, 700 mm

3) Step-up (One leg – stand straight)

Gradual shift in the angle while stooping down is correspondingly reflected in the adjustment of pressure at rear and front foot. Pressure signature captured by the BIG-MAT displayed in figure 4.2, represents the pressure distribution and associated location of CG with an acceptable limit of standard deviation for the sample population.

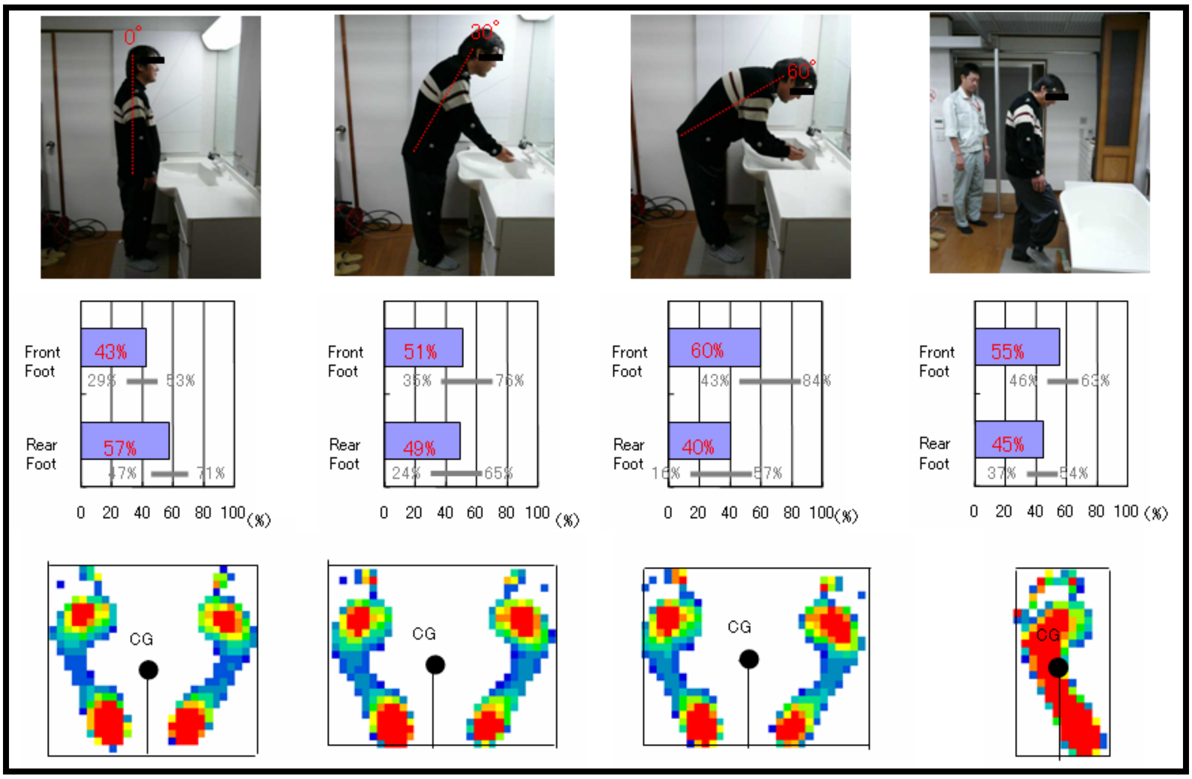


Figure 4.2 Pressure exerted at front and rear foot (middle image) and CG location (bottom image) of the real human subjects

Figure 4.2 shows the location of CG for each selected postures and the middle image shows the weight distribution and the standard deviation (SD) of all the tested subjects.

4.1.3 Digital Human Versions of the Subjects:

Digital human versions of the monitors are also being made and figure 4.3 shows the location of center of mass (CG). The middle image in the figure shows the distribution of total weight in front and rear foot. In different body postures the position of CG and the pressure on the front and rear foot remains unchanged. But for maintaining balance during variable postural conditions, adjustment of CG is required as well as the pressure experienced on the rear and front foot will change accordingly.

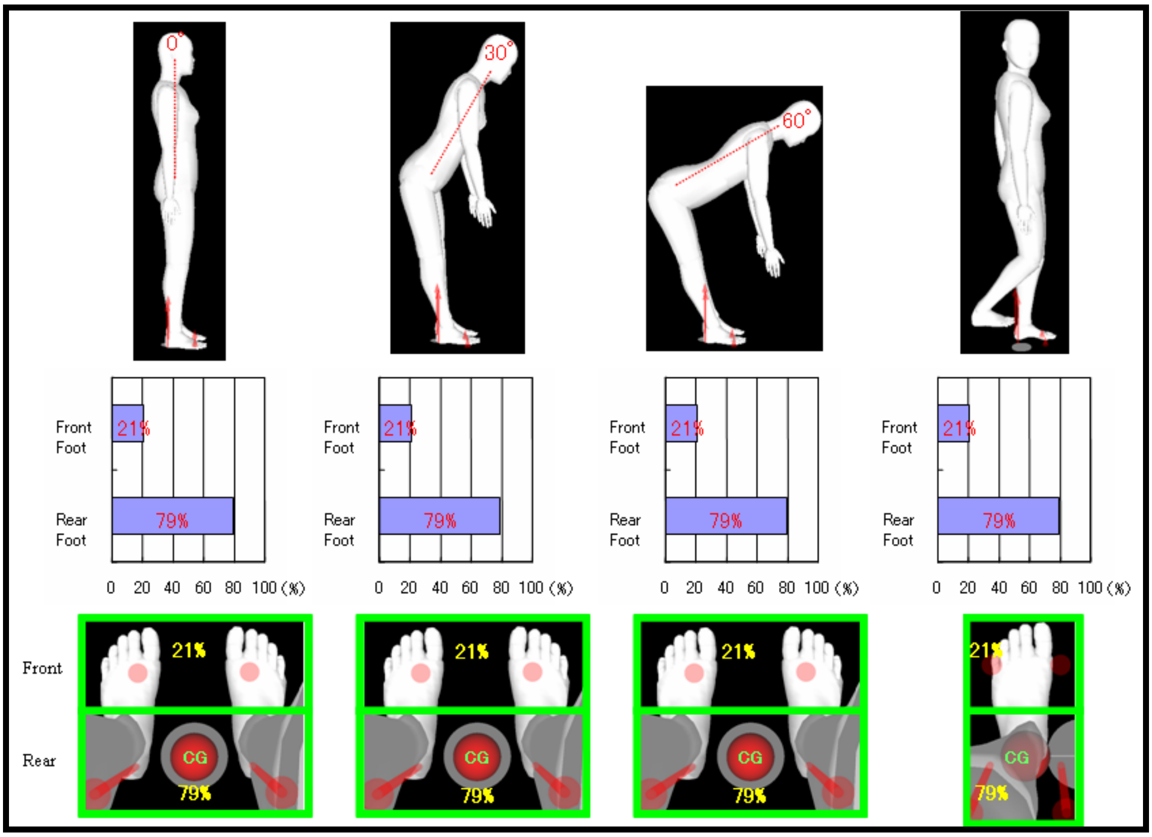


Figure 4.3 Digital Human versions of the monitors showing the pressure at front and rear foot and the location of CG

4.1.4 CG correction for digital human models

Based on the results obtained by real-human tests, the necessity of correctly positioning center of mass (CG) and the support values at the front and rear foot of digital humans is understood and the strategy is planned as shown in Figure 4.4. Based on the outcome of the real subjects (monitor) depicted in figure 4.2, correction of CG position and adjustment of the pressure at rear and front foot is performed alternatively for different body postures of the digital human model.

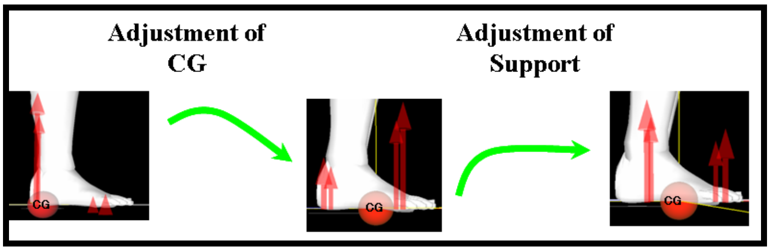


Figure 4.4 Strategy for correcting the location of CG of digital humans

After aforesaid correction, performance of the monitor, performance of the digital human prior to the correction of CG and pressure adjustment at feet, correction of CG without adjustment of support and performance of digital human after overall correction (four scenarios shown in different colors) has been depicted in the following graph for each body postures. Figure 4.5 shows the percentage of weight experienced by the front foot for each scenario.

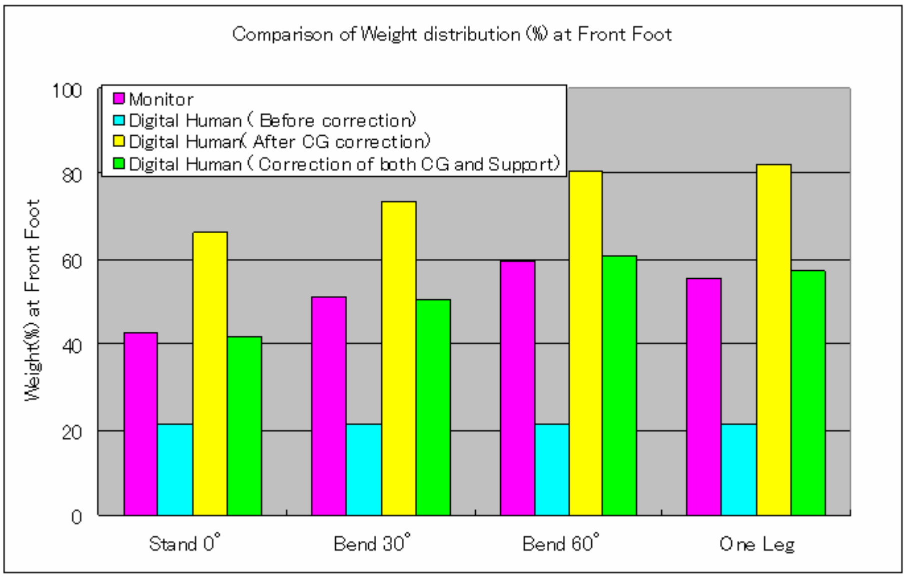


Figure 4.5 Correction Results – Weight (%) at the front foot

Figure 4.5 shows the corrected values. The bar in the chart (colored pink) is the percentage of weight distribution at the front foot of the real humans, and the green colored bar in the chart is that of digital human after validation.

Efficiency of digital human in maintaining postural balance in different condition is shown by the above figure (figure 4.5) where weight at front foot both in digital human and real human is approximately equal for each posture of the body. While the uncorrected and partially corrected readings glaringly points towards deviation from monitor readings (real human performance), incorporation of alternative correction in CG and support adjustment for the digital human shows approximate correspondence with real human test.

CG location of the digital human is also being corrected with that of the monitor, taken as a percentage of the total foot length for different body postures in all four scenarios. Figure 4.6 shows the comparison of CG location as a percentage of foot length.

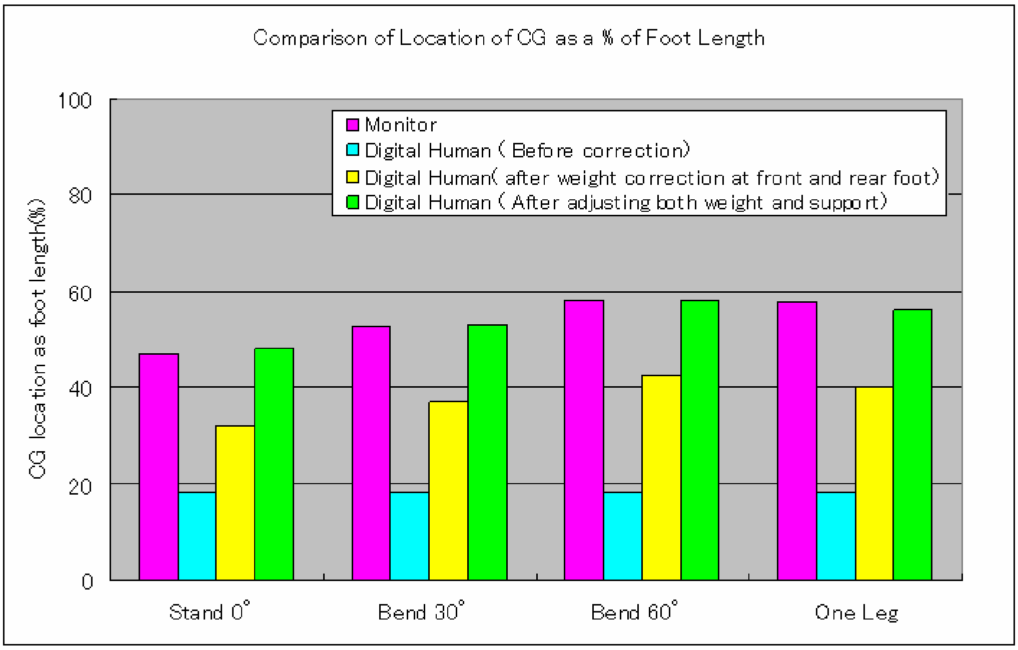


Figure 4.6 Correction Results – CG location

Analysis of CG location depicted in figure 4.2 for real human test and subsequent correction incorporated along with uncorrected value of the digital human shows approximate correspondence for different body postures. CG location for the concerned scenario is taken as a percentage of the total foot length.

Figure 4.6 shows the corrected values. The bar in the chart (colored pink) is the location of CG as percentage of foot length of the real humans, and the green colored bar in the chart is that of digital human after correction.

Figure 4.7 shows the corrected digital human models for the location of center of mass (CG) and weight distribution. Performance of the corrected digital human model on comparing with the real human test results pictorially represented in figure 4.2 demonstrates the efficacy of correction in CG and support adjustment process. With this correction, digital human model almost displays the approximately the same characteristics as that of a real human for all four body postures.

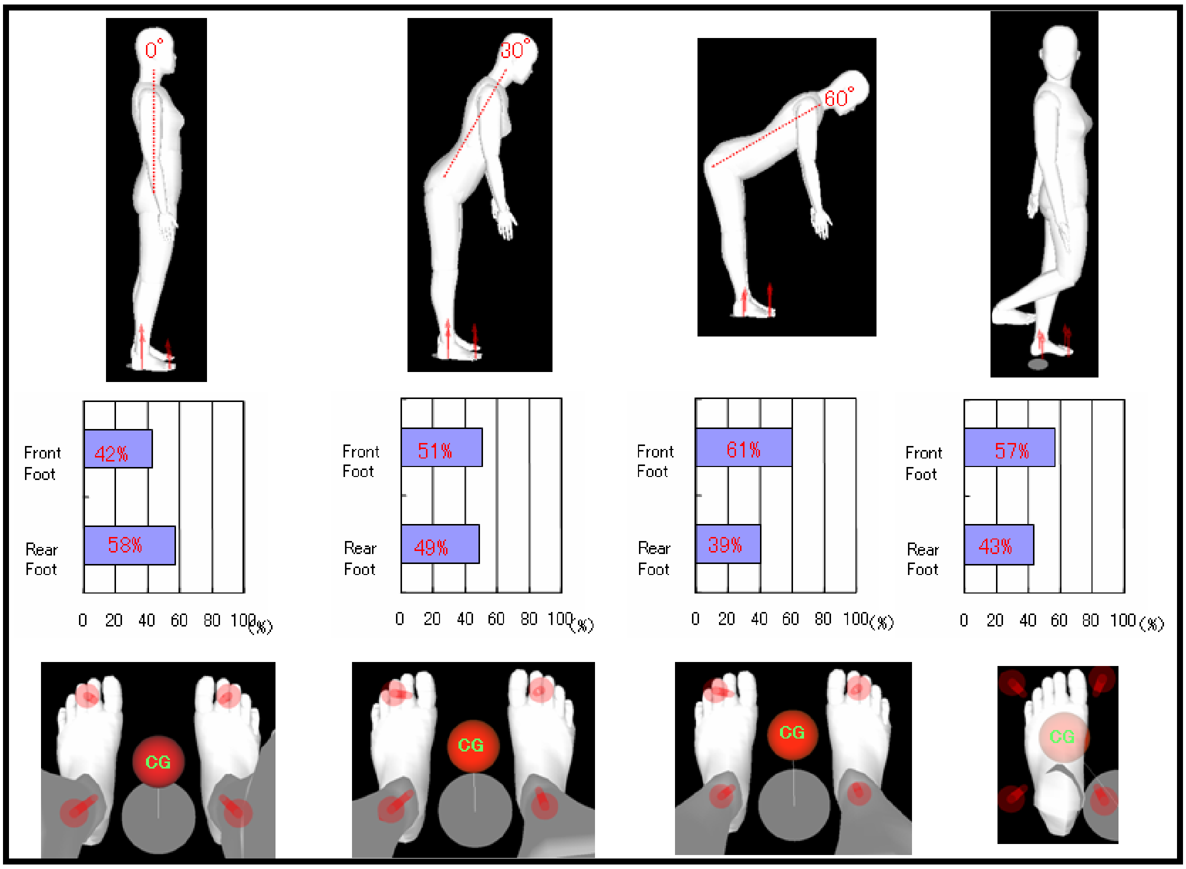


Figure 4.7 Digital Human model – Corrected for CG location /weight distribution at the foot

4.1.5 The influence on stability of standing posture by age factor

Considering the fact that for any human posture, pressure experienced by the foot varies within two extreme limits, i.e. forward and backward leaning extremes. Capacity of a human to maintain balance within this range of extremes also depends upon the ageing factor. So centre of foot pressure in different body postures is a function of range of extreme backward and forward leaning, and age. The influence of these two factors are reported by the seminal work of Katsuo Fujiwara [KAT 82], that have been incorporated further in our digital human models as shown in Figure 4.8. The graph shows the influence on stability of standing posture by age factor, which in turn indicates the safe range of Centre of pressure at the foot between extreme backward leaning posture (EBLP) and extreme forward leaning posture (EFLP) as a function of age at x-axis. For a young human this safe zone of maintaining balance is large while gradually getting constricted on moving to older ages.

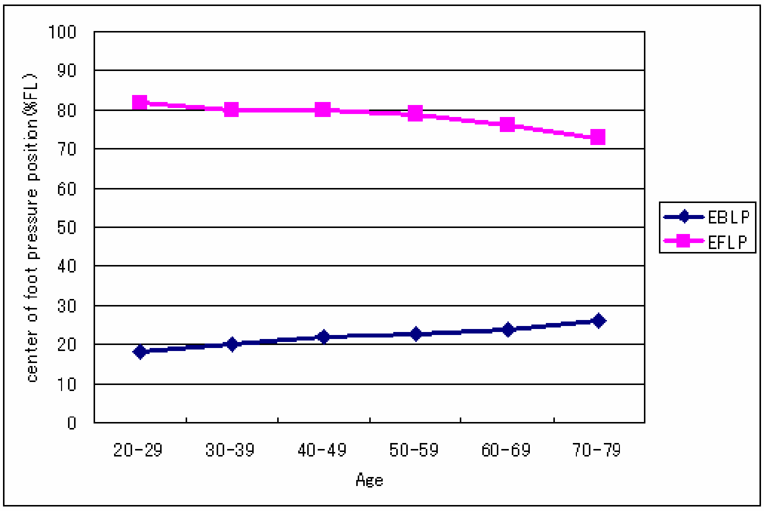


Figure 4.8 Center of foot pressure position (as a % of Foot length) for extreme backward and extreme forward leaning postures at different ages

Position of center of pressure i.e. CG, as a percentage of foot length lies in the range confined between the EBLP and EFLP lines for erect body posture. Location of CG for digital human in erect body posture, depicted in the figure 4.6, lies close to the fifty percent of the total foot length.

4.2 Analysis and verification of the Torque exerted at the shoulder

Towards the validation of torque exerted by the digital human model we aim to determine the correspondence between the force exerted by the real human subjects and that of digital human during a pulling down operation of the kitchen shelf. To get the maximum accuracy of the process, force exerted by the subjects has been estimated by two way approaches, using psychological response of the subjects and the EMG test performed on one of the subjects. Psychological response rating varies from 0 to 3, corresponding to the difficulty level from zero to maximum. Torque exertion on the digital human in the shelf pulling down operation is then compared with the performance of real human obtained from psychological feedback and EMG pick-up.

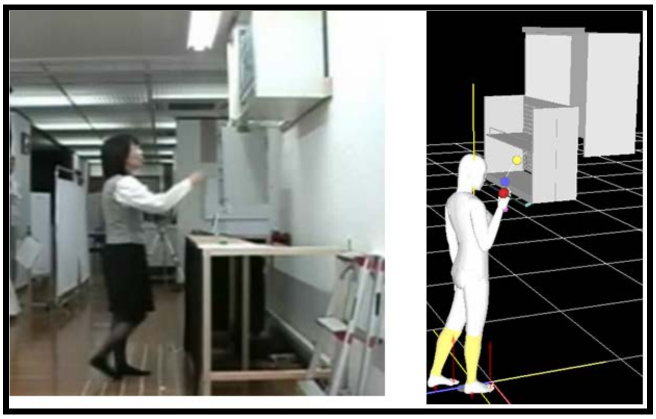
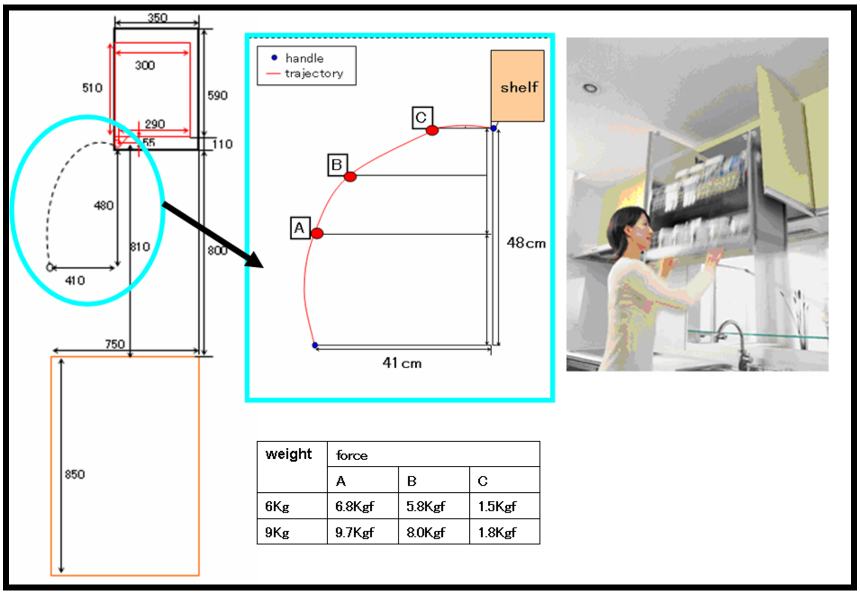


Figure 4.9 Real & Virtual human shelf pulling down operation.

4.2.1 Scenario setup for validation

Focused application is as shown in the figure 4.9, a pull-down shelf of a kitchen. The factors for comparing the results were set up as the following.

Total weight of the shelf has been kept as 6 kg and 9 kg and their equivalent weight experienced at three control points A, B, and C have been set at a pre-set value provided in the table contained in the figure 4.10. Dimension of the pull down shelf and trajectory of the shelf movement are as shown in figure 4.10



weight	force		
	A	B	C
6Kg	6.8Kgf	5.8Kgf	1.5Kgf
9Kg	9.7Kgf	8.0Kgf	1.8Kgf

Figure 4.10 Environment set up – Pull down shelf

For the experiment, 6 subjects (including 3 young and 3 old people) were selected between the height range of 1.5M and 1.8M, weight range of 50 Kg and 70 Kg. Subjects were requested to have their comfortable posture during the experiment from the two given choices; Normal standing posture with both leg together or the posture with one leg forward. All the six subjects were comfortable with the posture with one leg forward. Accordingly we have selected the one-leg forward posture pattern.

4.2.2 Psychological feedback analysis of the subjects

First, a sample of real humans performed a task where they reached up and pulled down the shelf. After performing the task, they were then asked to assign a value of zero to three to the amount of exertion put on different parts of their body with zero being no exertion and three being maximum exertion**.** Values assigned to psychological responses from sample of real humans felt at different body points during pull down operation, ranging from easy to difficult denoted by numbers 0, 1, 2, 3 has been shown pictorially in figure 4.11

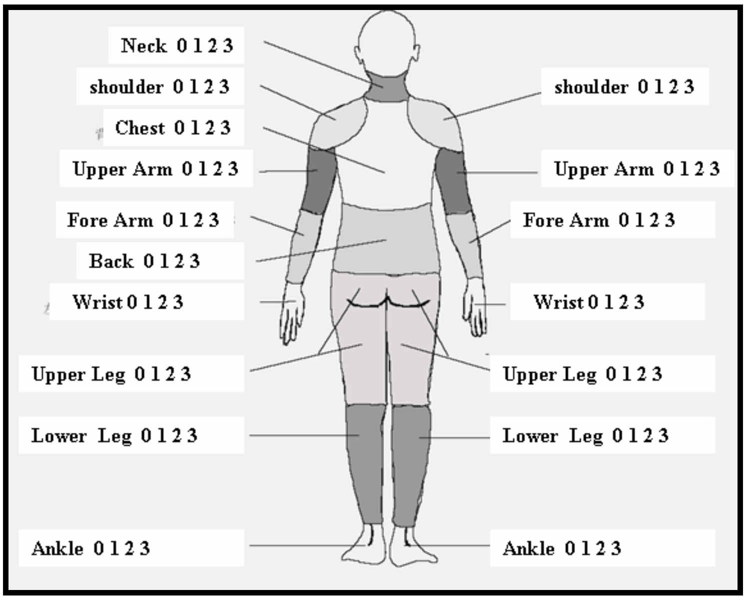


Figure 4.11 Value assignments for the different part of the body of monitors toward the amount of exertion of the pull-down task

Feedback of actual values of psychological response obtained from real human of old and young age subjects has been listed in table 4.1. Various responses felt at shoulder (SH), upper arm (UA), fore arm (FA) etc. at three control points for two different weight configurations are shown in the table.

Weight of the Shelf	monitor	A							B							C						
		Body Parts							Body Parts							Body Parts						
		SH	UA	FA	WR	BA	KR	KL	SH	UA	FA	WR	BA	KR	KL	SH	UA	FA	WR	BA	KR	KL
6K	Young1	2	2.5	2.5	1	0	0	0	2	0.5	0.5	1	0	0	0	0	0	0	0.5	0	0	0
	Young2	2.5	2	3	1.5	1.5	1	0	1	1	2	1.5	1	0	1.5	1	0	0	0	0.5	0	0
	Young3	1	2	2	2	1	0	0	2	2	1	1	0	0	1	1	1	0	0	0	0	0
	Old1	0	0	2	0	0	0	0	0	0	0	0.5	0	0	0	0	0	0	0	0	0	0
	Old2	0.5	0	0	0.5	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
	Old3	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0.5	0.5	0	0	0
9K	Young1	2.5	1.5	2	2.5	0.5	0.5	2	1	0.5	0.5	2	0.5	0.5	2	0.5	0	0	0.5	0	0	0
	Young2	2	3	2	2	1	1	1.5	1	2	2	1	0.5	0	1	1	0.5	0.5	0.5	0.5	0	0
	Young3	3	3	3	3	1	1	0	2	2	2	2	0	1	0	1	1	1	1	0	0	0
	Old1	0	0	1	2	0.5	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
	Old2	2	1	0	2	0	0	0	2	2	2	2	0	0	0	0	0	0	0	0	0	0
	Old3	0.5	2	2	0	0	0	0	0	0	0	2.5	0	0	0	0	0	0	0	0	0	0

Table 4.1 the values provided by the subjects while reaching at the control points A, B and C (for the weight of the shelf 6kg and 9kg)

4.2.3 EMG pick-up analysis of the subjects

Experimental setup shown in figure 4.10 is designed to measure the exertion experienced at fore arm, upper arm and the shoulder during pulling down operation of the shelf through EMG response pickup obtained from associated channels representing different body parts. Some participants were fitted with EMG pickups to record muscle activity during the task (Figure 4.12)

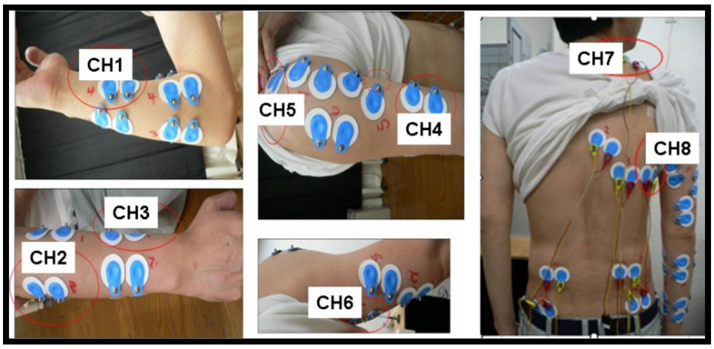


Figure 4.12 EMG pickup set up of the real human.

EMG pick-up response derived from channels for each control points A, B and C is further plotted as a bar-graph. Horizontal axis shows the control point locations A,B and C, while the vertical axis showing the EMG values in micro volt. The values obtained for each EMG channels (Channels 1 through 8) are shown in different colors in the bar graph. Psychological response felt at different control points by the same subject for fore arm, upper arm and shoulder is also merged in Figure 4.13 as line-graph. The vertical axis on the right side of the figure shows the values ranging from 0 to 3, zero being feeling of very easy and three, the feeling of very difficult.

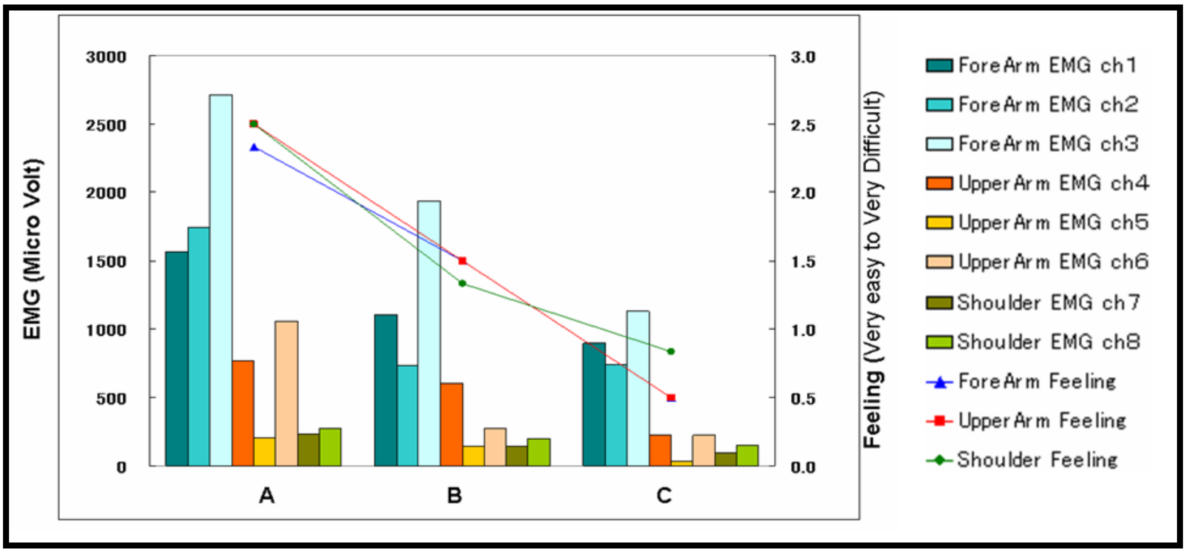


Figure 4.13 Results of the real subjects, bars representing EMG pickup and lines showing psychological feedback at the control points A, B, C.

Each EMG pickup obtained from different channels represents the exertion experienced at the concerned body part during shelf pulling down operation. EMG responses of each body part for the three control points are compared with the psychological responses of the human subject in the pulling down operation shown in the graph (figure 4.13). Psychological responses of feeling at fore arm, upper arm and shoulder are shown with differently colored lines. Graph in figure 4.13 shows that the exertion on the various body parts is in consonance with the pre-set level of weight assigned according to table in figure 4.10 for three control pointes denoted by A, B, and C. Amount of exertion felt is reducing from control point A towards C. EMG pickup bar-graph and psychological response line-graph is following the desired trend.

4.2.4 Virtual scenario analysis for the digital human

The digital human of each subjects are also being made with equivalent age, height, waist and arm length and the simulation is being carried out with the same weight input for the pull-down shelf. Performance of the shelf pull-down operation is shown in the following bar graph (figure 4.14) indicating decreasing trend of torque exertion experienced by the digital human shoulder and elbow at control points A, B and C.

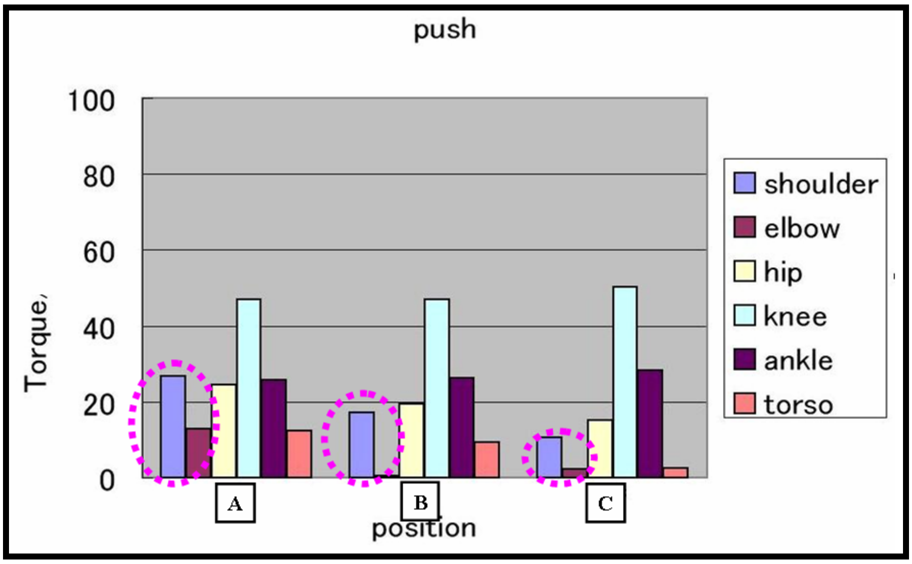


Figure 4.14 Results of Digital humans (gradual decrease in the shoulder torque is shown with dotted circle)

Muscle activity and reported results from real humans corresponded well to modeled responses from the virtual human with both reporting decreasing amounts of exertion for the selected static location A, B and C as shown in the figures (Figure 4.13 and 4.14). Decreasing trend of exertion experienced on the shoulder of the digital human at control points A, B and C is in consonance with the trend demonstrated by graph in figure 4.13. A minor change in posture can be seen affecting the values of torque at other associated joints such as knee and hip etc. due to transmission of stress at various joints through the articulated link structure. By carefully watching the posture of real-human subjects posture of each digital humans are also setup by trial and error. Please refer Appendix B for the changes in torque values especially in Hip and Knee joints due to minor change in the postural variation.

4.3 Conclusion

A mock-up experiment using real human subjects is conducted and based on the feedback of the experiment; validation of the biomechanical model is done through correction and adjustment of critical parameters. After adjustment and modification of the parameters the developed biomechanical model shows near perfect correlation with real human data, indicating the efficacy of our approach, which also shows conformity with the associated hindrance in the extreme forward and backward leaning position, seeping in through the old age [figure 4.8] in erect position coincidently. Profile of the torque exerted at the shoulder joint during shelf-pulling down operation for real human and digital human are also in consonance [figure 4.14].

Section C

Flexibility and Strength Estimation Based on Age

Chapter 5

Strategy Plan for Estimating Flexibility and Strength of Digital Human Based on Age

5.1 Introduction

For ergonomic applications, the developed articulated biomechanical model will not be sufficient to analyse the human factors if we do not have a method by which designers can compare whether the joint torques generated by digital human for a particular posture is permissible or within the affordable limits. These methods should include the comparison techniques for a single digital human as well as for the ageing population. Chaffin [CHA 99] has compiled Joint Moment – Strength Mean prediction equations for an average human, but those equations are not enough when we deal with whole population. Our strategy of strength analysis includes the estimation of three variables ***based on age*** and they are 1) Maximum Voluntary Contraction (MVC) 2) Joint Passive Resistance (JPR) and 3) Affordable Voluntary Contraction (AVC).

MVC is an isometric contraction representing strength. MVC is the peak force produced by a muscle as it contracts while pulling against an immovable object.The measure can be a exertion of force or moment around a joint.

JPR is a passive resistance against rotation of a joint. This resistance is caused by the soft tissues around the joint such as ligaments, tendons, and articulated capsule. It is often measured as moment around the joint according to the joint angle or angular velocity by rotating the joint without the activities of muscles.

Affordable voluntary contraction (AVC) is construed here as the permissible threshold of strength generated during a normal mechanical operation in which the person do not experience exertion beyond comfortable limit. This threshold of strength may vary from person to person due to age or other physiological factors involved. An intuitive and intelligent universal design would inherently respect this threshold strength.
.
The strategy plan to compare and categorize the possible physical strength is explained with shoulder as an example is shown in Figure 5.1

Permissible zone (Easy zone) are shown in Green, a little difficult zone is represented as yellow and when the shoulder reaches at the joint extremes or when the load/muscle strength reaches nearby the MVC, the zone is shown as Red zone (Very difficult). The limits of each zone would also vary due to ageing too. Similar strategy is planned for other joints also.

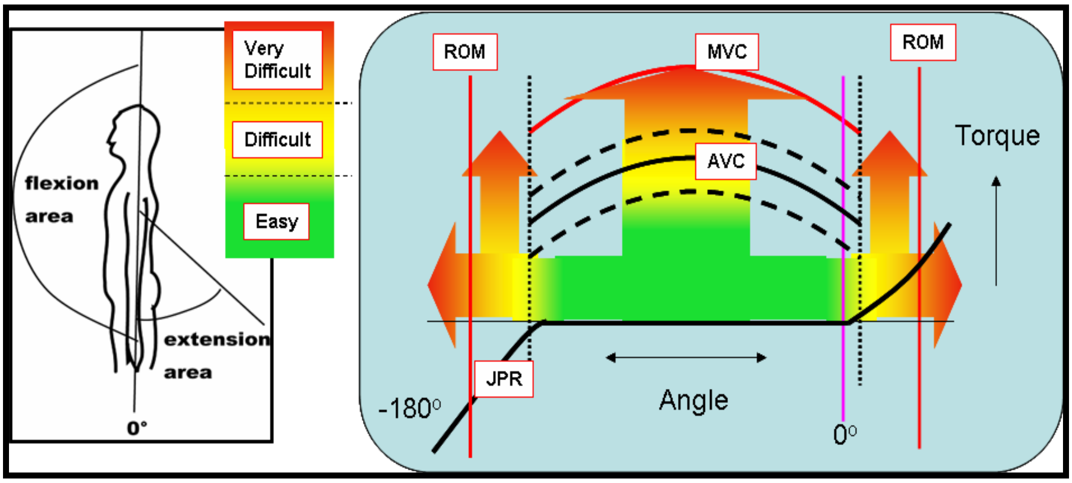


Figure 5.1 Strategy for estimating the affordable strength and flexibility zone of digital human shoulder

AVC estimation as a percentage of MVC along with the relative JPR for the whole population containing people of diverse age groups having varied values of MVC and JPR has to be done. In this regard, we carried out a quantitative analysis to strength estimation by making use of a physical characteristic database of actual human subjects. The database utilized for the strength estimation does not include AVC values as such, for its calculation further experimental analysis has been planned with real human subjects.

The strength is being estimated by using a database developed by National Institute of Technology and Evaluation (Osaka, Japan) [NIT 02] [HIS 07] and is publicly available since 2002. The following section introduces the database.

5.2 Physical Characteristic Database (NITE)

5.2.1 Origin of the Statistics

The database developed by National Institute of Technology and Evaluation, Osaka, Japan is publicly available since 2002. Human basic characteristics data for body size, physical fitness, and range of voluntary motion of the joints, passive counteraction of joints, maximum strength, and the functional power of the upper limbs are disclosed for 1000 examinees in a healthy condition having age in the range of 20 to 80 years. The database consists of six parts: Basic human body measurements (BHBMS), maximum voluntary contraction (MVC), and manual strength (MS), range of motion (ROM), joint passive resistance (JPR) and physical strength (PS). Statistical values such as average or standard deviation can be outputted with these data.

Subjects were randomly selected from Osaka, Nagoya, Kanazawa, Tokyo, Sendai and Fukuoka and test were performed in six NITE laboratories in these cities. None of the subjects were aware of having any neuromuscular, musculoskeletal, or cardiovascular disease. Based on the assumption that the older subjects would have a broader distribution of values, a large number of subjects aged 60 to 79 years old were enrolled. The demographic composition of the subjects is shown in Figure 5.2

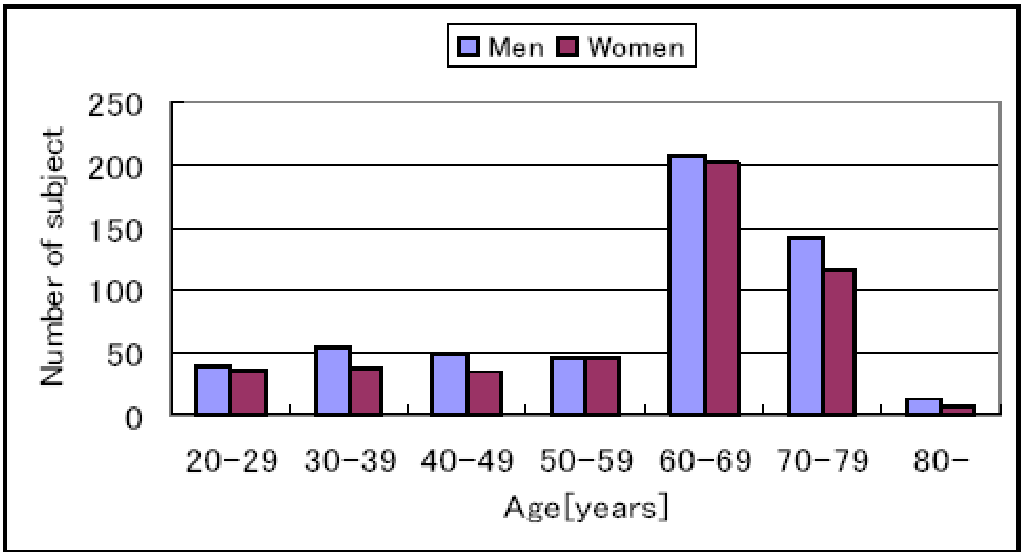


Figure 5.2 Composition of the subjects in NITE database

Measurements were made on 1000 Japanese men and women of age ranging from 20 to 84 years are selected and recruited nationwide. The range of height of the men was 163.3±6.82 [cm] and that of the women was 152.3±6.37 [cm]. The range of body weight of the men was 62.3±10.4 [kg], and that of the women was 52.2±7.4 [kg]. The database is publically available [NIT 02]

5.2.2 Collection Method

Dynamometers, such as Biodex, Cybex or Primus, have been extensively used to make measurements. To avoid instrumental stress on the elderly subject, a strain-gauge type compact force sensor from Kyowa Electronic Inst. Co. was used as a hand held dynamometer (HHD) to measure the Extreme Joint Torque (EJT) values in the upper limbs. It was attached to the measurement chair to measure the EJT values in the lower limbs. Sample measurement has been pictorially shown in figure 5.3 and 5.4.

A strain-gauge type compact force sensor (LPR-A-1KNS1, Kyowa Electronic Instruments Co., Tokyo) was used as a hand-held dynamometer (HHD). HHD was held by the examiner in the measurement of upper limbs and a HHD was attached to the measurement chair to make the lower-limb force measurements, because lower limb force values are high, and it is difficult for the examiner to hold the HHD steady.

Figure 5.3 MVC Measurements during knee extension.

The MVC data posted in the NITE database are isometric measurements made in the sagittal plane. A sagittal plane is a longitudinal plane that divides the body of a bilaterally symmetrical animal into right and left sections. The data described in the NITE database are maximum force and maximum torque measurements, and the torque measurements were gravity compensated by taking mean of the body segment parameter. MVC measurements were made of limb joints (hand, elbow, shoulder, ankle, knee, and hip). An example of taking measurement of MVC during knee extension is shown in Figure 5.3

MVC measurements of the joints in each extremity were made on the subjects' right side by means of isometric Make-Test tests in the sagittal plane. Each trial consisted of a 4- to 6-second's contraction. The MVC measurements were made under the subjects' "Expiring" in order to prevent strokes caused by sudden changes in blood pressure. At least one minute of rest was allowed between each trial.

The Joint Passive Resistance JPR data posted in the NITE database are torque values measured during rotation of the joint without the activities of the muscles. The JPR data, except for the shoulder joint and hip joint were measured in the sagittal plane, and the shoulder joint and hip joint data are reported for the sagittal plane and horizontal plane. An example of measurement for shoulder flexion in the sagittal plane is shown in Figure 5.4 (middle image). The first image shows the MVC measurement set up and the last one, the Range of motion for the Elbow.

Figure 5.4 measurements example of MVC, JPR and ROM respectively

The ROM data posted in the NITE database are for active range of motion. The ROM data, except for the shoulder joint and hip joint were measured in the sagittal plane, and the shoulder joint and hip joint data are reported for measured in the sagittal plane and horizontal plane

5.2.3 Reliability of the data

The reliability of anthropometric data is primarily determined by three factors**:** sampling bias; skill of the measurer and data editing. The sampling bias is the degree to which the measured subjects are not representative of the population. If the skill of the measurer is sufficient, the measurements are repeatable and the values obtained are similar to those obtained by a skilled anthropometrist. Data editing is necessary to eliminate erroneous values caused by various mistakes.
Random sampling helps prevent sampling bias, but most surveys do not include random sampling. When the target population is 100% Japanese, the magnitude of the sampling bias can be evaluated by comparing data obtained for mean height and weight between the survey in question and a national survey conducted by the Japanese government.

It is unrealistic to think of eliminating errors entirely in gathering data. In order to minimize this, the database is made public after deleting the erroneous data from the original files. For example, if there is a data of which the standard deviation is more than 4σ, then it is deleted with the confirmation of its 3 Dimensional image data

Towards implementation of the proposed strategy, input of the physical characteristic database (NITE) are used in the next chapter for strength estimation and development of the age correction coefficient for mean strength of male and female falling in different age groups.

Chapter 6

Quantitative Estimation of Ageing Algorithm

The muscle strength of the limbs makes a crucial difference in the activities of the daily life from a physical stand point. While the major challenge for maintaining the independent life of elderly people comfortable today is the development of user-friendly products and environments with universal design, etc., so that the elderly can live without difficulty even with little muscular strength. The database developed at National Institute of Technology and Evaluation (NITE) is helpful to compare the muscle strength of the limbs of Japanese across age groups and to assess age-related differences in the muscle strength of the limbs.

6.1 Maximum Voluntary Contraction (MVC)

The data consists of the average values of two trials of performance of the subjects. MVC values were measured with each joint forming 3 to 4 different angle, because extreme joint torque values vary with the angle formed by the joint.

Elbow flexion and extension were made with the subject seated with the shoulder joint at 0 degrees and the forearm in the hammer grip position. Shoulder flexion and extension were made with the subjects seated with the elbow joint at 0 degrees and the forearm in the hammer grip position. Knee flexion measurements were made with the subject in the prone position and the hip joint at 0 degrees. Knee extension measurements were made with the subject seated and the hip joint at 90 degrees. Hip flexion and extension measurements were made with the subject in the supine position and the knee joint at 90 degrees. The angle between the trunk and thigh was adjusted to 90 degrees whenever the subject was in the seated position.

Figure 6.1 shows the variation of maximum strength of the subjects and the standard deviation for each age group. These readings for muscle strength, in NITE database are taken at an angle where the torque generation is maximum, recorded in flexion and extension actions, both for men and women.

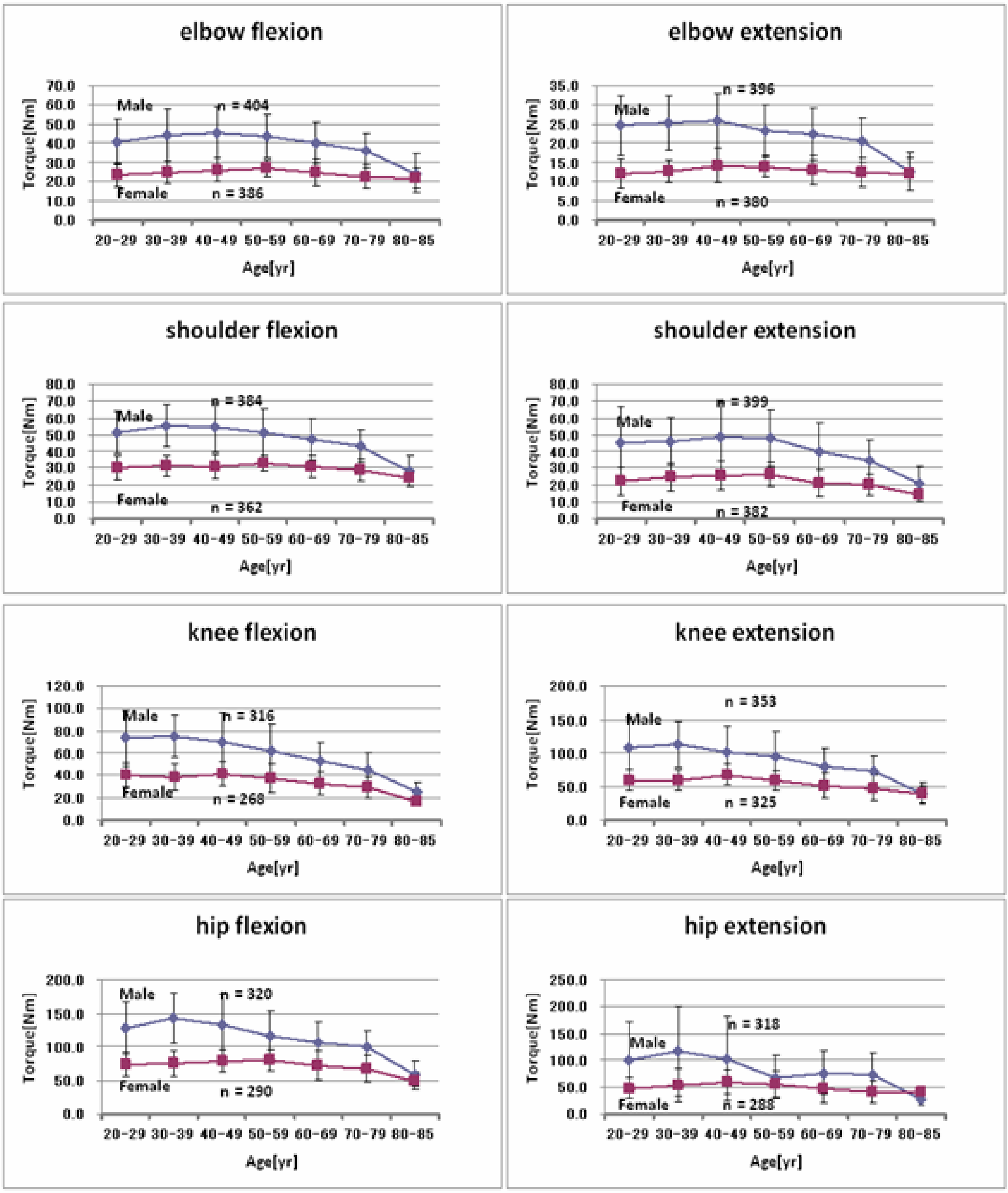


Figure 6.1 Variation of Maximum Strength of the subjects and Standard deviation (SD) for each age layer for Elbow, Shoulder, Knee and Hip Joints (Red line – Female, blue line – male)

Measurement angles available in the database are shown in Table 6.1. It lists the flexion and extension angles on which the muscle strength of elbow, shoulder, hip and knee has been recorded in the NITE database. Please refer to Appendix C-1 for angle convention

	flexion			extension			
Elbow	60	100	150	60	120	150	
Shoulder	35	80	130	35	80	130	
Hip	90	135	165	75	90	135	
Knee	90	130	165	75	90	105	130

Table 6.1 Measurement angles available in the database

6.1.1 Observation and noticed peculiarities

Top two figures (In Figure 6.1) for elbow flexion and extension shows the trend of decreasing the maximum strength with advancing age, for both sexes. Trend for shoulder flexion and extension for both sexes displays same pattern. While the muscle strength for the women changes in a very small amount over the life-span, for men the muscle strength gradually withers away as they age. In case of knee, the graph show substantial decline in the muscle strength for men with increase in age. During hip flexion and extension the muscle strength is shown with a zigzag graph which is declining towards the older ages. The zigzag shape is more pronounced in the case of men while the women graph shows almost smooth trend. *Interestingly, these figures clearly demonstrate the peculiarities of the bodies of men and women*.

The results of measurements in about 1000 subjects showed significant differences in muscle strength between the men and women. Examination of differences among age groups revealed the largest MVC values in the subjects in their 30s, 40s, or 50s in both men and women. *The younger group of both men and women tended to have lower MVC values than the subjects in the age groups in their 40s and above. These points towards a startling fact that present younger generation do not possess the same robust physique that early generations enjoyed.* Many younger man and women these days can be seen sitting or leaning against objects in railway stations, classroom etc. and this phenomenon may be attributable to the lower muscle strength of younger generation. Many labor-saving devices, such as washing machines, vacuum cleaners and refrigerators made life more comfortable and convenient but over-automated and excessively labor-saving devices have diminished opportunities for muscle training during housework and daily life. Moreover the younger generation is not much into sports, and many of them are on diets. Off course, these labor saving devices and such concepts as ‘universal design’ or ‘design for all’ are essential for ageing societies.

6.1.2 Data analysis and formulation of joint mean-strength equations

Figure 6.2 shows the interpolated values for extreme joint torque at different angles and the lines with different colors are plotted in the same graph for each age group for elbow and shoulder. Please refer to Appendix C-2 for the interpolated values of remaining joints.

Using the concept that, to maintain static equilibrium at each joint, there exists a measurable muscle-produced strength moment that should not be exceeded by the moment exerted by the external loads, we can develop a biomechanics based model that predicted human strength. One of the first static coplanar (sagittal-plane) models predicting strength was developed by Chaffin (1969) for the analysis of load-lifting activities. Based on the analysis of the interpolated MVC values, developed Joint Moment-strength mean Prediction equation for each age layer for elbow and shoulder flexion and extension are shown in Table 6.2 and Table 6.3. Developed joint moment-strength mean prediction equations are functions of the angle (α) made at the respective joint.

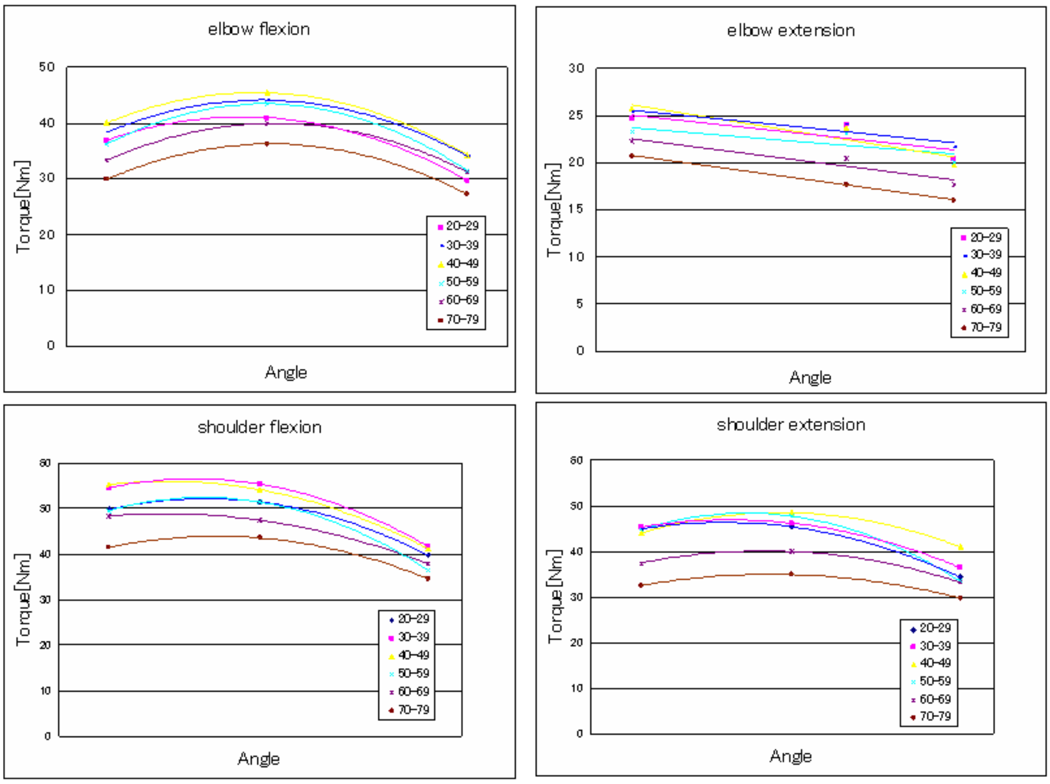


Figure 6.2 Interpolated MVC values for elbow and shoulder for different age groups

Age	Strength (Elbow)	Predicted Mean Strength (Nm)
20 ~ 29	flexion	$S_f = -0.0036\,\alpha_E^2 + 0.6763\,\alpha_E + 9.3617$
	extension	$S_e = -0.0416\,\alpha_E + 27.581$
30 ~ 39	flexion	$S_f = -0.0038\,\alpha_E^2 + 0.7521\,\alpha_E + 6.965$
	extension	$S_e = -0.0377\,\alpha_E + 27.799$
40 ~ 49	flexion	$S_f = -0.004\,\alpha_E^2 + 0.7728\,\alpha_E + 8.005$
	extension	$S_e = -0.0622\,\alpha_E + 29.914$
50 ~ 59	flexion	$S_f = -0.0046\,\alpha_E^2 + 0.9213\,\alpha_E - 2.335$
	extension	$S_e = -0.0307\,\alpha_E + 25.538$
60 ~ 69	flexion	$S_f = -0.0037\,\alpha_E^2 + 0.7635\,\alpha_E + 1.045$
	extension	$S_e = -0.0485\,\alpha_E + 25.494$
70 ~ 79	flexion	$S_f = -0.0037\,\alpha_E^2 + 0.755\,\alpha_E - 1.8717$
	extension	$S_e = -0.0519\,\alpha_E + 23.863$

Table 6.2 Predicted Mean-Strength equations for each age layer for Elbow

Age	Strength (Shoulder)	Predicted Mean Strength (Nm)
20 ~ 29	flexion	$S_f = -0.0029\,\alpha_S^2 + 0.3646\,\alpha_S + 40.536$
	extension	$S_e = -0.0024\,\alpha_S^2 + 0.2865\,\alpha_S + 37.888$
30 ~ 39	flexion	$S_f = -0.0031\,\alpha_S^2 + 0.3683\,\alpha_S + 45.42$
	extension	$S_e = -0.0022\,\alpha_S^2 + 0.2741\,\alpha_S + 38.493$
40 ~ 49	flexion	$S_f = -0.0025\,\alpha_S^2 + 0.2607\,\alpha_S + 49.128$
	extension	$S_e = -0.0026\,\alpha_S^2 + 0.4026\,\alpha_S + 33.167$
50 ~ 59	flexion	$S_f = -0.0035\,\alpha_S^2 + 0.4477\,\alpha_S + 38.298$
	extension	$S_e = -0.0037\,\alpha_S^2 + 0.4902\,\alpha_S + 32.157$
60 ~ 69	flexion	$S_f = -0.0018\,\alpha_S^2 + 0.1841\,\alpha_S + 44.116$
	extension	$S_e = -0.002\,\alpha_S^2 + 0.2896\,\alpha_S + 29.817$
70 ~ 79	flexion	$S_f = -0.0024\,\alpha_S^2 + 0.3154\,\alpha_S + 33.342$
	extension	$S_e = -0.0016\,\alpha_S^2 + 0.2384\,\alpha_S + 26.191$

Table 6.3 Predicted Mean-Strength equations for each age layer for Shoulder

For the estimated equations for the remaining joints, please refer Appendix C-2

6.1.3 Ageing equations – mean strength for male and female

Chaffin [CHA 99] has compiled Joint Moment-Strength Mean prediction equations for an average human and the Table 6.4 lists mean strength prediction equations and type of strength curve for the main joints of the human body.

STRENGTH st = g(θ)	JOINTS	EQUATION (units: Nm)	TYPE OF CURVE
Elbow flexion	Elbow and shoulder	$(336.29+1.544\theta_E-0.008\theta_E^2-0.5\theta_S)\ 0.1913$	Asc-desc
Elbow extension	Elbow and shoulder	$-(246.153-0.575\theta_E-0.425\theta_S)\ 0.2126$	Descend.
Shoulder flexion	Shoulder and elbow	$(227.338+0.525\theta_E-0.296\theta_S)\ 0.2845$	Ascend.
Shoulder extension	Shoulder	$-(204.562-0.099\theta_S)\ 0.4957$	Asc-desc
Seated torso flexion	L5/S1	$-(141.179 + 3.694\theta_T)\ 0.2796$	Asc-desc
Seated torso extension	L5/S1	$(3365.123 - 23.947\theta_T)\ 0.3381$	Asc-desc
Standing torso flexion	L5/S1	$-(17.17\theta_T - 0.079\theta_T^2)\ 0.2146$	Asc-desc
Standing torso extension	L5/S1	$(3894 - 13.9\theta_T)\ 0.1559$	Asc-desc
Hip flexion	Hip	$(-820.21+34.29\theta_H-0.114\,26\theta_H^2)\ 0.1304$	Ascend.
Hip extension	Hip	$-(3338.1-15.711\theta_H+0.04626\theta_H^2)\ 0.0977$	Descend.
Knee flexion	Knee	$-(-94.437+6.3672\theta_K)\ 0.1429$	Ascend.
Knee extension	Knee	$(1091.9-0.0996\theta_K+0.17308\theta_K^2)\ 0.0898$	Asc-desc

Table 6.4 Joint moment strength mean prediction equations compiled by Chaffin for an average human (for both genders)

But those equations are not enough when we deal with whole population having people of different age group. In this regard, we intend to introduce a quantitative approach to strength estimation by making use of a physical characteristic database of actual human subjects. The ageing equations have been derived for each age group (table 6.2 and 6.3). From figures (eg: Figure 6.2) it is clear that the strength measured as the torque at concerned joint for each age layer is having a different amplitude in the graph. The relative variation of strength over age layers is calculated by measuring the amplitude of each layer and taking the top one of them fixed as a reference. The deviation of other age layers in relation to the reference layer is thus obtained. For each joint this procedure is followed and a convenient reference age layer is taken. At every joint, the average relative deviation of age layers with the reference age layer is calculated as **Age Factor (AF).**

The derived coefficients for predicted mean strength for different ages are then merged with Chaffin equations as age correction coefficients (AF). Table 6.5 and table 6.6 show the modified mean-strength equations corrected for different age groups and genders.

Joint	Predicted Mean Strength (Nm) for Japanese Male
Elbow Flex	$S = (168.3[AF] + 1.544\,\alpha_E - 0.0085\,\alpha_E^2)*0.1913$
Elbow Ext	$-S = (155.7[AF] - 0.575\,\alpha_E)*0.2126$
Shoulder Flex	$S = (218.2\,[AF] - 0.296\,\alpha_S)*0.2845$
Shoulder Ext	$-S = (105.8[AF] - 0.099\,\alpha_S)*0.4957$
Hip Flex	$S = (-1452.6[AF] + 34.29\,\alpha_H - 0.11426\,\alpha_H^2)*0.1304$
Hip Ext	$-S = (2115.5[AF] - 15.711\,\alpha_H - 0.04626\,\alpha_H^2)*0.0977$
Knee Flex	$S = (-524.1[AF] + 6.3672\,\alpha_K)*0.1429$
Knee Ext	$-S = (485.2[AF] - 0.0996\,\alpha_K + 0.17308\,\alpha_K^2 - 0.00097\,\alpha_K^3)*0.0898$
Joint	**Predicted Mean Strength (Nm) for Japanese Female**
Elbow Flex	$S = (197.9[AF] + 1.544\,\alpha_E - 0.0085\,\alpha_E^2)*0.1005$
Elbow Ext	$-S = (157.4[AF] - 0.575\,\alpha_E)*0.1153$
Shoulder Flex	$S = (241.7[AF] - 0.296\,\alpha_S)*0.1495$
Shoulder Ext	$-S = (113.1[AF] - 0.099\,\alpha_S)*0.2485$
Hip Flex	$S = (-1632.1[AF] + 34.29\,\alpha_H - 0.11426\,\alpha_H^2)*0.0871$
Hip Ext	$-S = (2058.8[AF] - 15.711\,\alpha_H - 0.04626\,\alpha_H^2)*0.0516$
Knee Flex	$S = (-565.3[AF] + 6.3672\,\alpha_K)*0.0851$
Knee Ext	$-S = (342.8[AF] - 0.0996\,\alpha_K + 0.17308\,\alpha_K^2 - 0.00097\,\alpha_K^3)*0.0603$

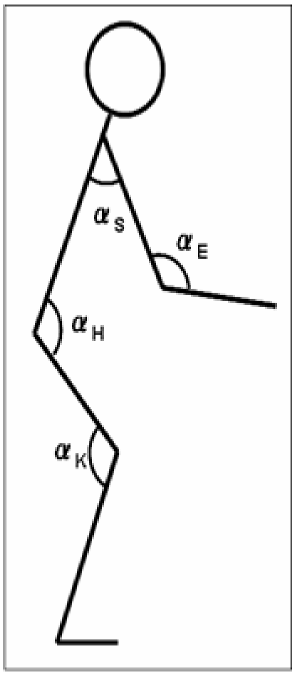


Table 6.5 Derived equations for MVC values for each joint (Elbow, Shoulder, Hip and Knee) for different age groups

Age correction coefficient for joint mean-strength at hip, shoulder, elbow and knee joints are calculated for male and female subjects falling in the different age groups as shown in Table 6.6

Age (Male)	Elbow		Shoulder		Hip		Knee	
	Flex	Ext	Flex	Ext	Flex	Ext	Flex	Ext
20-29	0.861	0.965	0.937	0.940	1.080	0.917	1.023	0.889
30-39	0.958	0.986	1.000	0.955	1.000	1.000	1.000	1.000
40-49	1.000	1.000	0.981	1.000	1.055	0.934	1.074	0.730
50-59	0.937	0.924	0.937	0.985	1.143	0.762	1.174	0.592
60-69	0.828	0.896	0.872	0.838	1.187	0.806	1.296	0.229
70-79	0.714	0.848	0.810	0.740	1.227	0.787	1.404	0.099
80-85	0.344	0.603	0.563	0.470	1.440	0.563	1.660	-0.686

Age (Female)	Elbow		Shoulder		Hip		Knee	
	Flex	Ext	Flex	Ext	Flex	Ext	Flex	Ext
20-29	0.820	0.881	0.934	0.852	1.042	0.895	1.021	0.623
30-39	0.892	0.920	0.960	0.950	1.034	0.949	1.058	0.603
40-49	0.961	1.000	0.954	0.972	1.009	1.000	1.000	1.000
50-59	1.000	0.981	1.000	1.000	1.000	0.969	1.081	0.590
60-69	0.884	0.933	0.949	0.821	1.056	0.895	1.175	0.236
70-79	0.779	0.902	0.894	0.782	1.092	0.839	1.254	0.061
80-85	0.739	0.879	0.764	0.592	1.217	0.825	1.518	-0.370

Table 6.6 Age correction coefficients (Age Factor – AF) for mean strength for male and female in different age groups

6.1.4 Discrepancy noticed and the plausible explanation

Peculiarity of the age correction coefficients for the age groups 50-59, 60-69 and 70-79 in comparison to people falling in the younger age groups can be explained on the basis of data provided in the NITE database, which clearly remarks that the older generation was physically sturdier due to more physical activities. While the younger generation which relies mostly on the mechanized system in the daily basic physical necessities has seemingly made them internally weaker in strength, the older generation's manual practices coupled with more outdoor sports activities enabled them to retain the strength even at the older age.

6.2 Affordable Voluntary Contraction (AVC)

To estimate affordable strength of an individual at a particular age, the available database was not sufficient and we did further experiments with hundreds of different subjects using Biodex System (Figure 6.3).

	extension	flexion
Shoulder	30°	30°
Elbow	90°	120°
Hip	15°	105°
Knee	15°	75°

Figure 6.3 Snapshots of the method of estimating AVC using Biodex system.

6.2.1 Method of estimating AVC

AVC measurements of the joints in each extremity were made on the subjects` right side by means of isometric “make” tests in the sagittal-plane. Each subject was asked to exert all their strength only to the extent that they did not think 10 repetitions of the exertion would bring continued pain/fatigue to their muscle, instead of their MVC. A muscle strength measurement system (Biodex System 3 : BDX-3) was used in AVC measurements. Based on the psychological response of the subjects and the readings of BDX-3 system affordable strength estimation is recorded.
Total number of subjects were 104 (consisting of 32 young and 72 old subjects) and the AVC is determined as a percentage of MVC for each joint. Total number of subjects and their AVC values with corresponding Standard deviation are shown in Table 6.7.

Young : N=32 (Age 30~48)

	%MVC	S.D.
Elbow flexion	48%	18%
Elbow extension	50%	15%
Shoulder flexion	57%	14%
Shoulder extension	50%	16%
Hip flexion	52%	15%
Hip extension	29%	14%
Knee flexion	48%	18%
Knee extension	42%	18%

Old : N=72 (Age 60~72)

	%MVC	S.D.
Elbow flexion	53%	17%
Elbow extension	58%	17%
Shoulder flexion	65%	16%
Shoulder extension	65%	13%
Hip flexion	63%	16%
Hip extension	52%	18%
Knee flexion	61%	19%
Knee extension	57%	17%

Table 6.7 Total number of subjects tested (N) for both Young and Old and AVC values as a percentage of MVC

The bar graph in Figure 6.4 shows the values for the selected angle for each joint and the AVC as percentage of the MVC is plotted for young and old subjects for respective joints. From the data shown in table 6.7 and bar-graph pattern, it is found that affordable strength of older subjects is higher than that of younger subjects! This result further corroborates the fact that the present younger generation is having less of muscle strength as compared to the older one.

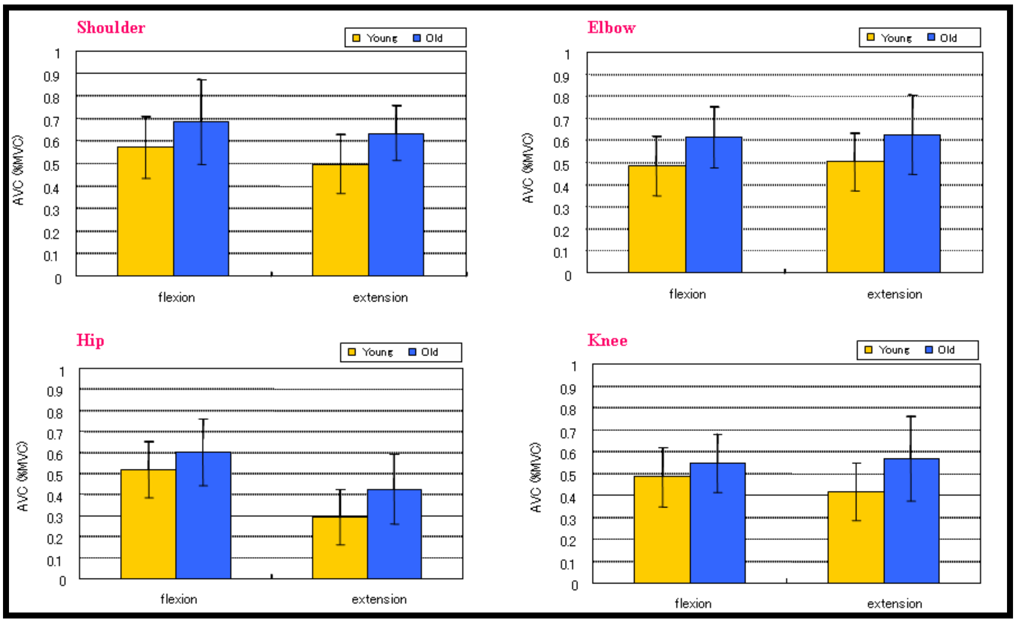


Figure 6.4 AVC as a % of MVC (both Young and old)

6.3 Joint Passive Resistance Analysis (JPR)

For passive resistance (JPR), the data has been analyzed near the joint extremes and age related parameters are developed. These are useful for making decisions when any joint of digital human reaches joint limit. The strategy for the passive torque (Joint Passive resistance) is described in Figure 6.5. An exponential function for Joint moment to angle can be expressed as the following

$$\mathbf{T = k_1 \exp\{ k_2 (\theta - k_3) \} - k_4 \exp\{ k_5 (k_6 - \theta) \}}$$ **[19]**

Joint Passive resistance (JPR) for younger are shown as $\mathbf{T_y}$ and that of older are shown as $\mathbf{T_o}$ It is expected that the JPR for the older subjects increases faster than that of younger people while moving toward the joint extreme. Thus the aim of this analysis was to find out the angle (and or the slope) at which torque values shows the sharp turn from their normal values, which in turn would help us to identify the approximate cut-off between easy and difficult zone (green and yellow respectively), whereas very difficult (Red zone) could be determined by the Range of Motion (ROM) values.

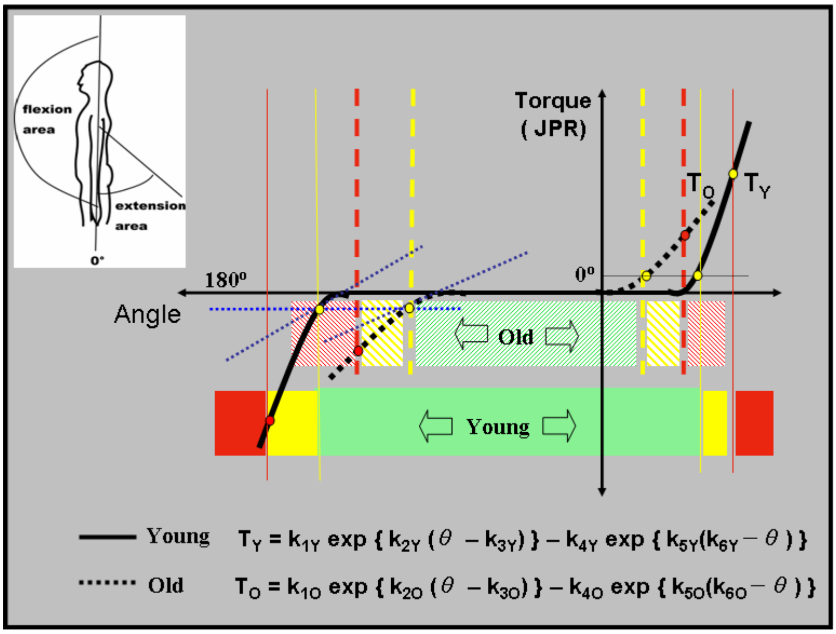


Figure 6.5 Strategy plan for estimating JPR for different age groups

The unprocessed data for each individual subject from the database has been analyzed with the exponential equations to determine the constants K1, K2, K3, K4, K5 and K6.

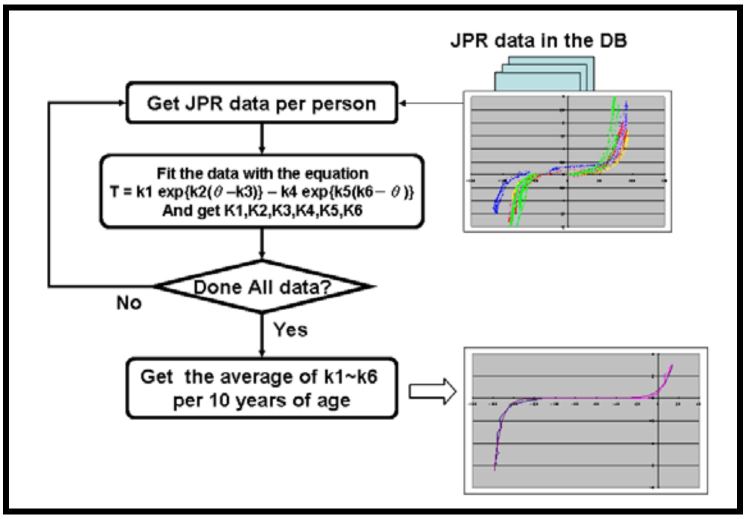


Figure 6.6 Method of estimating the K values from the raw-data

Figure 6.6 shows the block diagram for estimation the K values by curve fitting method, and the corresponding graphs for joint passive resistance at the shoulder for the associated age groups are shown in Figure 6.7

K values thus obtained for male and female of different age groups for shoulder joint from the exponential equation of the JPR are shown in table 6.8. For the remaining joints, kindly refer to Appendix C-3

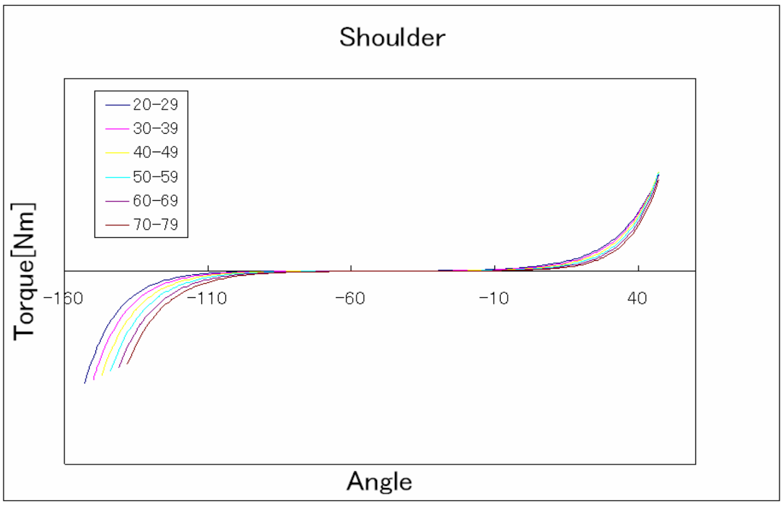


Figure 6.7 JPR graphs for Shoulder after analyzing the raw-data

Shoulder

Male	k1	k2	k3	k4	k5	k6
20-29	1	4.398078	0.5359	1	2.323534	-2.05819
30-39	1	4.228129	0.533515	1	2.471415	-2.02423
40-49	1	4.144547	0.387093	1	2.77157	-2.1636
50-59	1	4.188602	0.53077	1	2.989074	-2.12155
60-69	1	5.255715	0.551481	1	3.081762	-2.04166
70-79	1	4.840089	0.566879	1	2.748759	-1.98861
80-85	1	5.708097	0.708196	1	2.48617	-1.9412

Female	k1	k2	k3	k4	k5	k6
20-29	1	3.82196	0.671403	1	2.435457	-2.18614
30-39	1	3.879128	0.692687	1	2.61016	-2.22193
40-49	1	4.550033	0.545025	1	2.793225	-2.23361
50-59	1	5.000277	0.688817	1	2.747242	-2.26693
60-69	1	4.687634	0.609874	1	2.713124	-2.10024
70-79	1	5.042809	0.627791	1	3.245745	-2.16261
80-85	1	5.00773	0.623842	1	3.029854	-2.1354

Table 6.8 Estimated K values for different age groups for the shoulder Joint

The curves of exponential growth are determined by K3 and K6. It is found that K6 increases and K3 decreases when age increases. The slopes of the exponential growth are determined by K5 and K2. Slope increases for increased K5 and decreases for increased K2. It is expected that when age increases K5 decreases and K2 increases.

Comfort zone and the corresponding joint angle for each layer are determined by estimating the minimum torque at which the exponential growth begins by analyzing the RMS values of the slope with the following equation.

$$\Sigma |T(\theta_i)-Ti(\theta_i)|^2$$

The estimated values of cut-off for JPR at shoulder joint for male and female of different age groups has been listed in the table 6.9 based on the strategy introduced in the figure 6.5. Here JPR has been represented by the experienced torque along with the angle and the slope at which the torque encounters a sharp turn from the normal value with associated tolerance as root mean square value of the error. The values for the remaining joints are listed in Appendix C-4

Shoulder

Male	Flexion				Extension			
Age	angle	torque	slope	error	angle	torque	slope	error
20-29	-135	-1.993	-4.631	0.184	22	0.509	2.245	0.180
30-39	-132	-1.990	-4.918	0.208	21	0.490	2.079	0.160
40-49	-138	-1.965	-5.446	0.257	13	0.513	2.129	0.160
50-59	-135	-2.009	-6.006	0.305	21	0.502	2.102	0.160
60-69	-130	-2.007	-6.186	0.324	24	0.497	2.613	0.251
70-79	-128	-1.957	-5.380	0.252	25	0.530	2.567	0.227
80-85	-127	-1.977	-4.916	0.209	34	0.517	2.955	0.310

Female	Flexion				Extension			
Age	angle	torque	slope	error	angle	torque	slope	error
20-29	-139	-1.788	-4.355	0.181	33	0.692	2.648	0.183
30-39	-140	-1.777	-4.639	0.206	34	0.679	2.635	0.185
40-49	-140	-1.791	-5.002	0.238	26	0.659	2.999	0.248
50-59	-142	-1.781	-4.894	0.229	35	0.676	3.380	0.308
60-69	-133	-1.816	-4.927	0.228	30	0.666	3.122	0.266
70-79	-134	-1.764	-5.727	0.315	32	0.704	3.550	0.327
80-85	-133	-1.750	-5.302	0.273	32	0.720	3.604	0.329

Table 6.9 the angle, slope and the RMS error at which the exponential growth begins for each age group for the shoulder joint.

6.4 Torque at the torso and the maximum compressive force

Available database (NITE) does not include the maximum compressive force exerted or experienced by the torso because it is unlikely that any human will voluntarily agree for this break-test. But for the ergonomic analysis the biomechanical model needs to address the problem of the lower back pain resulting from different postures.

The spinal column is often the location of discomfort, pain and injury because it transmits many internal and external strains. Impact and vibrations from the lower body is transmitted primarily through the spinal column into the upper body and conversely forces and impacts experienced through the upper body, particularly when we are working with our hands, are transmitted downward through the spinal column to the floor or the seat structure that supports the body. So the function of spinal column in absorption and dissipation of energy from torso to the lower body is crucial. Aging also affects the spine as it does all skeletal components.

Our digital human is an articulated link model which lacks masculine structure of a human. The compression force experienced at the torso due to the impact of a mechanical operation done by the upper body should be within a comfortable and affordable limit.

By using available literature and equations [CHA 69] [FRE 84] [GAR 745] [GAR 79] [AND 85] [CHA 91] [JAG 97], the torque value in the digital human model has been compared with the torque at which the compressive force is maximal on torso (L5/S1) for each various age groups. The value of torque at which compressive force affordable limit is crossed has been calculated for each age group on the basis of Jager and Genaidy judgment method. The snapshots shown in Figure 6.8 are the real-time visualization of torque exerted at torso (the red dots in the graphs). The blue lines in the graphs show the maximum compressive force (Fc) and the red line, the corresponding torque at the torso. The maximum compression force and the corresponding torque value exerted at torso for different ages based on the judgment of Jager and Genaidy are listed in the Tables in Appendix D

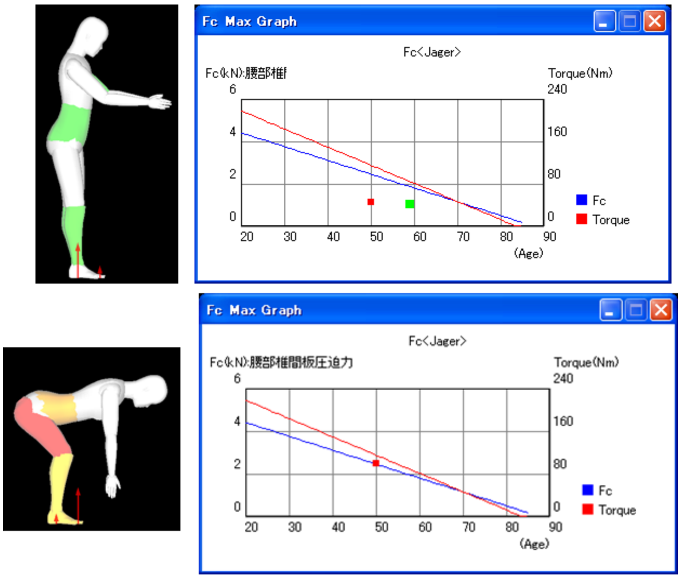


Figure 6.8 Comparison of torso torque with maximum torque at which the compressive force is maximal

6.5 Conclusion

This section introduced an approach to estimate the effect of ageing on articulation limits and physical strength at joint level by making use of a physical characteristic database of Japanese people. The derived coefficients for predicted mean-strength for different ages are then merged with Chaffin equations as age correction coefficients. These results and the effects of joint passive resistance (JPR) on ageing would be used in the upcoming chapters to evaluate the strength and flexibility for different postures at different ages. *The posture and motion of virtual humans due to ageing is beyond the scope of this dissertation.*

Section D

Postural Control Techniques and Total System as an Ergonomic Evaluation Engine

Chapter 7

Postural Control Techniques with Prioritized Inverse Kinematics Architecture

7.1 Introduction

Human postures can be characterized by at least three potentially conflicting requirements which are particularly important for a specific task (the corresponding constrained body part and goal are indicated into parenthesis):

- Maintaining the balance (the center of mass has to project in the support area),
- Viewing (eye gaze direction has to go through a target area),
- Reaching (hands have to reach a target location, carry or manipulate an object).

Based on the requirements of a particular task, Ergonomic designer has to choose a specific solution space (of the virtual human posture), which is not a simple task, as for even a simple reach task, different preferred envelope exists! Let us look in to the scenario in detail.

Preferred work area of hands and feet are in front of the body. Usually, it is represented by the curved envelopes, at least by the following four cases

- Mobility of the fore arm in the elbow joint
- Mobility of the Total arm in the shoulder joint
- Mobility of the lower leg in the knee joint
- Mobility of the total leg in the hip joint

These envelopes are often described as the partial spheres around the present location of the body joints. However, preferred ranges within the mobile zone are different when the main requirements are strength, speed, accuracy, vision etc. Even for a simple balanced standing reach posture, there could be many possible postures and some of them include the following as shown in the figure 7.1 which are self-explanatory.

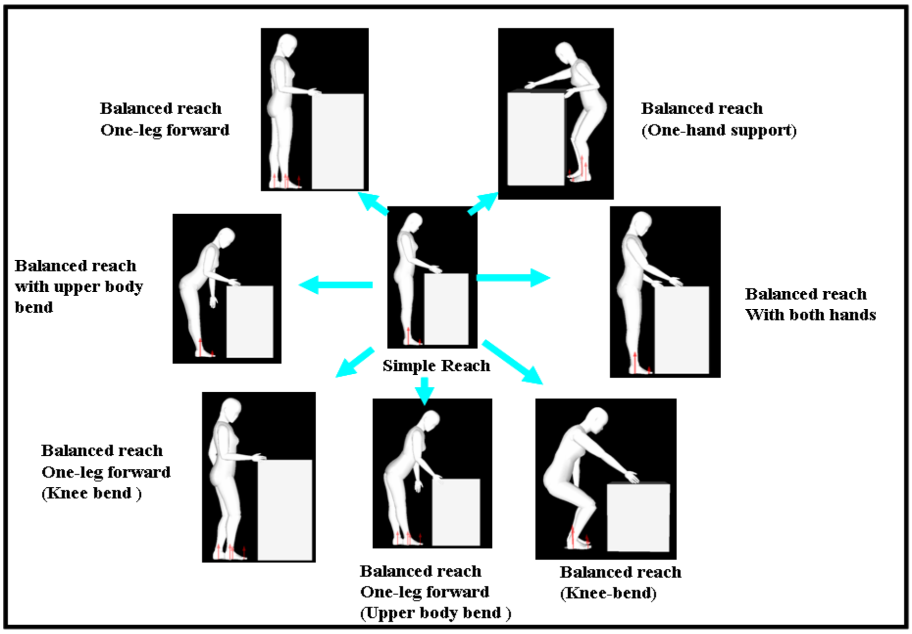


Figure 7.1 Standing Reach Task – A few possible posture configurations

Posture optimization techniques such as Prioritized Inverse Kinematics have demonstrated its capacity to enforce sets of position and/or orientation constraints organized within a hierarchy of priority [MOL 99]. For example, it has been successfully applied (off-line) to the systematic evaluation of the human reachable space in various contexts [ROD 03] [ROD 03a] [BOU 04]. In these studies, each context is characterized by a so-called "strategy" defining a fixed set of constraints associated to priorities. Those strategies were tested on one virtual manikin to achieve different classes of reach (seating, standing, crouching, on the toe tip). These prior efforts highlighted the importance of the task of setting the correct hierarchy of constraints; four to five constraints and priority levels were generally used to define a strategy for a default virtual manikin. The present work extends these efforts in the direction of generalizing the posture optimization to a whole population showing in particular a large range of height and ages. A complementary direction of our present investigation is the direct on-line interaction of end-users with the system. We allow non-specialists to choose a virtual manikin from a population and to evaluate its reach capability. For these goals a more versatile task definition has to be handled through more complex groups of constraints that fit to virtual manikin of any size.

7.1.1 Background

A common approach to control the posture of a virtual human is to enforce the constraints by associating them with independent set of joints; for example the root node is responsible for maintaining the balance, each arm is responsible for controlling the corresponding hand, and the neck chain is responsible for controlling the eye gaze direction. Fast analytic solutions are available for solving such simplified context [BAD 93a] [SHI 01]. However, such an approach also reduces the solution space in a way that prevents finding some pertinent solutions. This limitation is most likely to occur when all the constraints cannot be enforced simultaneously.

We advocate for a more *synergistic* approach where some constraints may share some joints to achieve their goal [BAE 04]. Conflicts among individual constraint solutions now become a central issue to solve as they may share common joint subsets.

For real-time or interactive applications, local optimization methods are preferred to the much more expensive global optimization methods even if there is a risk of getting stuck in a local optimum of the objective function. In computer graphics, Zhao et al. use an optimization method for the manipulation of an articulated figure: a nonlinear function (describing the degree of satisfaction of all constraints) is minimized under a set of linear equality and inequality constraints describing joint limits [ZHA 94]. An application of this method for the manipulation of articulated figures is integrated within the Jack system [PHI 91]. This system is representative of a weighted approach where constraints are associated with weights and the system converges to a compromise solution minimizing the corresponding weighted error. In the field of Robotics however, researchers have developed *task-priority strategies* to precisely arbitrate conflicts by establishing a clear priority order among the tasks [LIE 77] [HAN 81] [MAC 85] [SIC 91]. In this family of approaches, the architecture of the optimization solver is simpler but allows to associate a strict priority with a constraint. We have adopted this approach. The final solution is built owing to projection operators (briefly outlined in the next section) that guarantee the strict enforcement of high priority constraints first; low priority constraints being enforced in the remaining solution space. The architecture fully developed in [BAE 04] can enforce an arbitrary number of priority levels knowing however that the posture solution space has a finite dimension.

For example, in a standing reach task, the balance has to be enforced with the highest priority. Similarly, the viewing constraint has a higher priority than the reach because the subject has to look at the target location. In case a low priority constraint cannot be fully satisfied, the resulting error is also minimized.

7.1.2 Strategy

The motion of the digital human body is entirely controlled by the articulated structure. We aim at defining a few high level handles allowing driving synergistically the posture of a virtual human for different tasks. For that purpose we exploit Prioritized Inverse Kinematics to define constraints associated with a priority level so that important properties are enforced first (e.g. balance) while less important adjustments are made in the remaining solution space [BAE 04].

Our strategy for the real-time motion control of the whole body is briefly described with the abstract block diagram as shown in figure 7.2. The Core Engine for our postural control Techniques is the Prioritized Inverse Kinematics (IK) Architecture. To provide a modular environment to control the **IK-Engine** a framework has been set up to deal with the grouping of effectors by developing IK-Middleware-Engine which is built on top of the IK-Engine. By adding high level layers such as Rule Generation Engine and User-Interface layer, care is being taken to make sure that intuitive manipulation of the articulated systems by minimal interaction with the mouse is possible. The generation of realistic posture in real-time is achieved by enforcing a control scheme for the grouping of effectors while running the IK engine in the back ground. Underlying techniques are briefly described in the following sections.

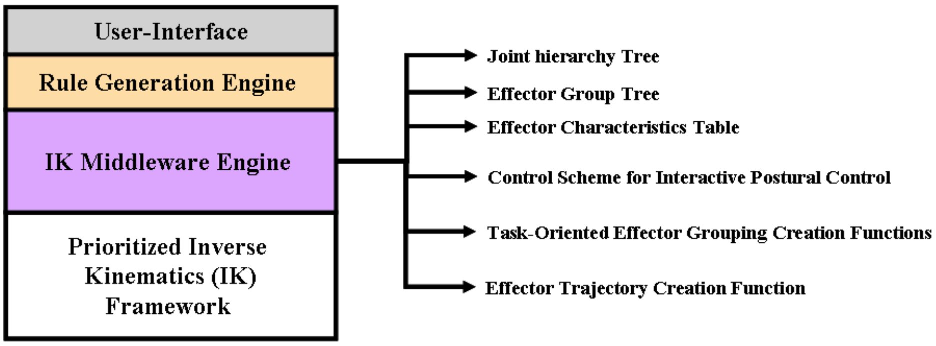


Figure 7.2 Outline of digital human motion control techniques

7.2 Prioritized Inverse Kinematics Framework

7.2.1 Outline of the Prioritized Inverse Kinematics Framework

Our general architecture is based on the linearization of the set of equations expressing Cartesian constraints $\boldsymbol{x}$ as functions of the set of mechanical degrees of freedom $\boldsymbol{\theta}$. We denote $\boldsymbol{J}$ the Jacobian matrix gathering the partial derivatives $\{\delta x/\delta\theta\}$. We use its pseudo-inverse, noted $\boldsymbol{J}^+$, to build the projection operators $P_{N(J)}$ on the kernel of $\boldsymbol{J}$, noted $N(J)$. Our approach relies on an efficient computation of projection operators, allowing to split the constraints set into multiple constraint subsets associated with an individual strict priority level [BAE 04]. The provided solution guarantees that a constraint associated with a high priority is achieved as much as possible while a low priority constraint is optimized only on the reduced solution space that does not perturb all higher priority constraints. For example, such architecture is particularly suited for the off-line evaluation of reachable space by a virtual worker; in such a context the balance constraint is given the highest priority while gaze and reach constraints have lower priority levels [BOU 04].

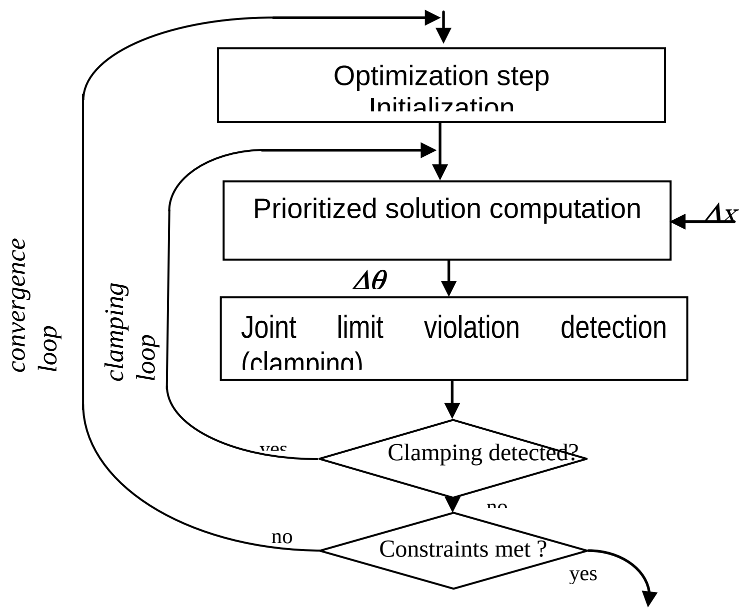


Figure 7.3: Outline of the constraint optimization loop integrating the Prioritized Inverse Kinematics together with a clamping loop enforcing the joint limits.

Figure 7.3 provides an overview of our Prioritized Inverse Kinematics Architecture. The outer convergence loop is necessary as the linearization is valid only within the neighborhood of the current state; this requires to limit the norm of any desired constraint variation Δx to a maximum value and to iterate the computation of the prioritized solution $\Delta\theta$ until the constraints are met or until the sum of the error reaches a constant value. This figure also highlights the clamping loop handling the inequality constraints associated to the mechanical joint limits. Basically we check whether the computed prioritized solution $\Delta\theta$ leads to violate one or more joint limits. If it is the case, equality constraints are inserted to clamp the flagged joints on their limit and a new prioritized solution is searched in the reduced joint space.

7.2.2 Enforcing Priority Levels among Constraints

For the sake of clarity, we assume that each independent constraint subset has a distinct priority level indexed by *i*, with 1 being the priority of highest rank, and *p* being the total number of priority levels. We denote J_i the Jacobian matrix gathering the partial derivatives $\{\delta x_i / \delta\theta\}$. The priority management needs to introduce an additional Jacobian matrix, called the *Augmented* Jacobian and noted J_i^A. It simply piles up all the individual constraint Jacobians J_i from level one to level *i* into one matrix. Our approach is based on the architecture described in [SS 91]. Nevertheless, we describe it with our more efficient evaluation of the projection operators.
Figure 7.4 summarizes the initialization stage which consists in computing the individual Jacobian, initializing the partial solution vector $\Delta\theta_0$ to zero and the projection operator to Identity. At that stage, all the joints are assumed to be within their limits, hence the initialization of the state flag to free.

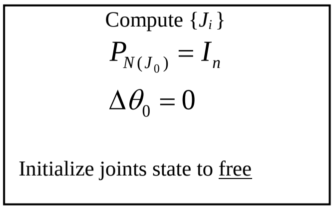


Figure 7.4: Optimization step initialization

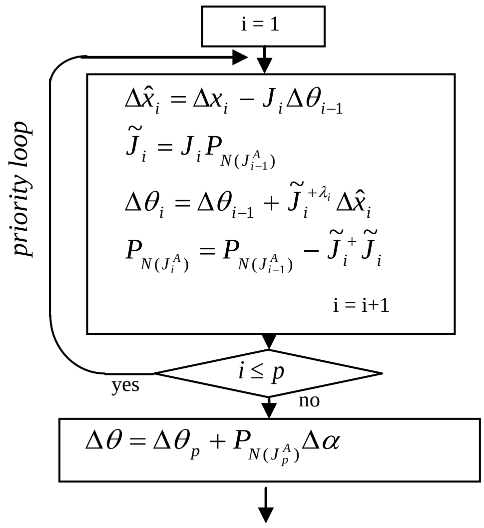


Figure 7.5: Computation of the prioritized IK solution

Figure 7.5 describes the priority loop; it explains the computation of the prioritized solution $\Delta\theta$ starting from the highest level contribution (for *i =1*) and adding one priority level contribution at a time. The contribution of each priority level *i* is decomposed as follow. First the compensated constraint $\Delta\hat{x}_i$ removes the influence of the higher priority levels, from *1* to *i-1*. Then we need an intermediate Jacobian $\tilde{J}_i$ which is the restricted Jacobian J_i to N(J_{i-1}^A); it ensures that we search for a solution only in the reduced solution subspace that does not perturb-ate all higher priority constraints from *1* to *i-1*. The cumulated solution up to level *i* is given by $\Delta\theta_i$. Afterwards, we update the projection operator $P_{N(J_i^A)}$ for the next priority level *i+1*. After the loop, we can add an optional criterion optimization term expressed in the joint variation space, noted $\Delta\alpha$.

When expressed as a function of the number of priority levels *p*, our recursive formulation has a linear computational cost compared to the quadratic cost of the previous formulation [SS91]. Its use results in a speed-up factor of roughly *(p+1)/2*.

7.2.3 Enforcing the joint limits (clamping loop)

As mentioned in 7.2.1, once the prioritized solution $\Delta\theta$ is obtained, we have to evaluate whether it leads to any joint limit violation (for the joints in the free state). When it is the case the joint state changes to the locked state because an equality constraint is set *on* the violated limit (clamping); as a consequence the joint is removed from the optimization step by adjusting the partial solution vector $\Delta\theta_0$ and the projection operator (Fig. 7.6). Then the optimization step is re-evaluated within this new context (Fig. 7.3).

```
Clamping detected = no
For each free joint in {j = 1,n}
   If θj update is over limit θLj
         Clamping detected = yes
     Δθ0j = ΔθCj          // fraction of Δθj that brings θj  on its limit value θLj
     θj = θLj
         zero j diagonal term of  PN(J0)
       statej changes to locked
```

Figure 7.6: Detection of the joint limit violation

7.3 Real-Time Interactive Postural Control

To provide a modular environment to control the **IK-Engine** (described above), a framework has been set up to deal with the grouping of effectors. The strategy was to deal with three main states.

1. Interactive control – Using a set of pre-defined effectors and Visual effectors
2. Automatic Reach Task – by generating Task-Oriented Effector Templates
3. Object Manipulation – by generating Effector Trajectories

Figure 7.7 shows the strategy for the 3 different basic functionalities

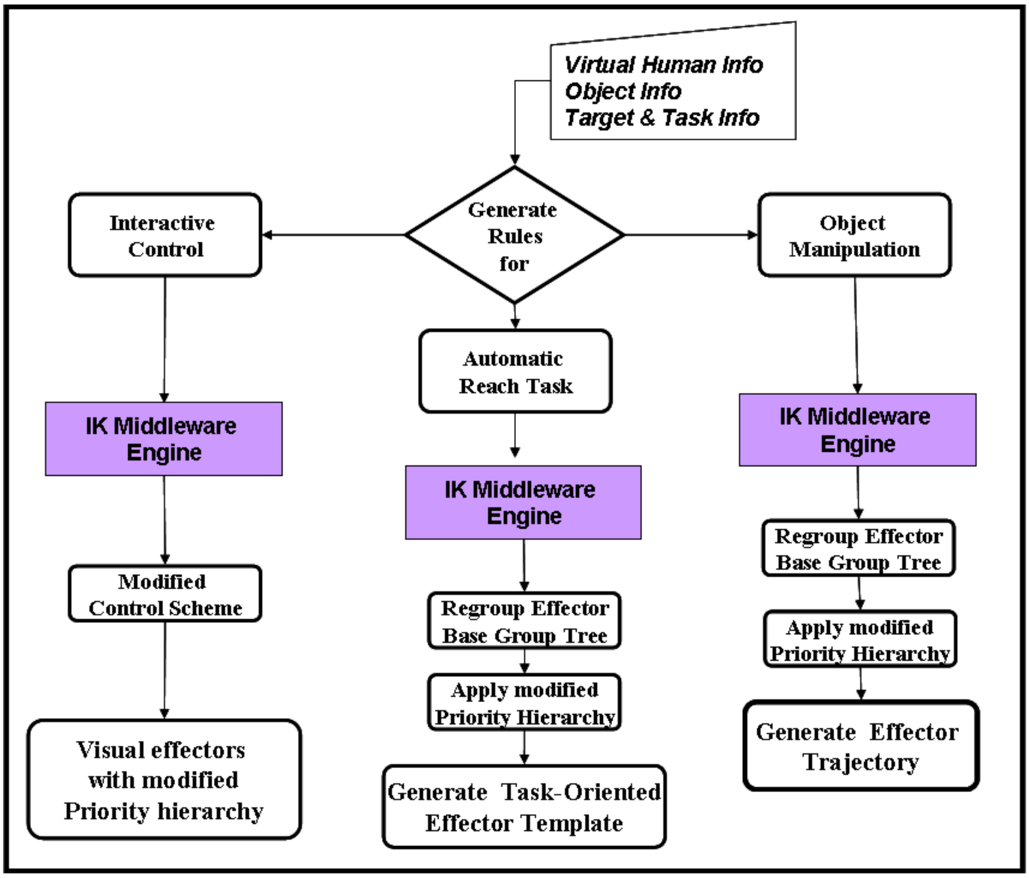


Figure 7.7 Strategy for the 3 different basic functionality (Interactive control, Automatic Reach task, Object Manipulation)

As shown in the figure 7.7, Real time postural control of the virtual human (VH) comprises of three comprehensive scenario handlings. **First**, interactive control for VH movement through mouse click and the final strategic outcome for this process is creation of visual effectors with modified priority hierarchy, dynamically updated for each possible posture of VH. Interactive control is at the joint interaction level. **Secondly**, for an automatic reach task performed by the VH, information about VH and the task are assigned by the designer and the strategic outcome for this process is the generation of dynamically modified and updated task-oriented effector template for various postural conditions. In **third** scenario, an object manipulation task framework is conceived based on the input information regarding VH and object and the strategic outcome of this process is the generation of effector trajectory using modified and dynamically updated priority hierarchy for each different posture.

IK-Middleware-Engine works as the core of the virtual human posture manipulation process and mainly consist of the following functional components

7.3.1 Joint hierarchy tree

It is articulated structure of a rigid body connected by joints, representing a hierarchy of nodes that denotes either a joint. The upper body of a joint can be defined as the sub-structure whose nodes are descendants of the joint, and the lower body of the joint as the complementary sub structure. The hierarchy tree is conceived taken humanoid root as the center and lower body and upper body locations are represented in a horizontal direction from left to right. The purpose of the joint hierarchy is to conveniently modify and update the joint characteristics such as priority, weight, and recruiting level of each joint. The joint hierarchy is shown in the Figure 7.8

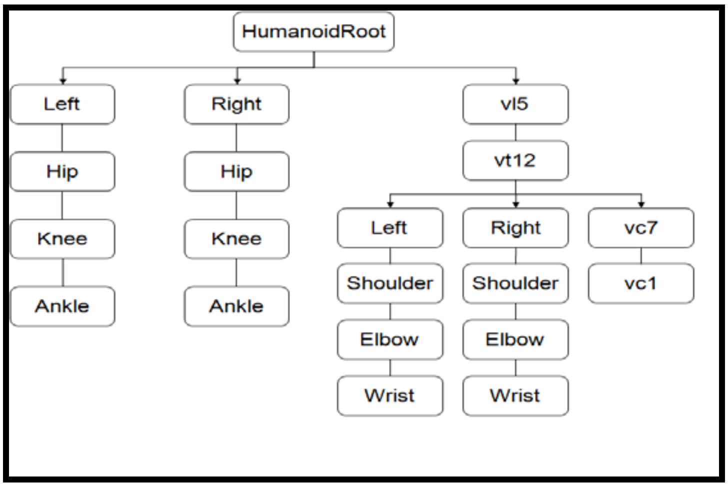


Figure 7.8 Joint – Hierarchy Tree for dynamically updating the joint parameters

7.3.2 Effector-group tree

Effector group base tree consists of groups of effector-joints, which provides for the working of virtual human at a layer higher than the individual joint during automatic reach task. Once the information regarding the virtual human and the task is provided, for automatic reach operation, the effector-group base tree is regrouped each time according to the input requirements.

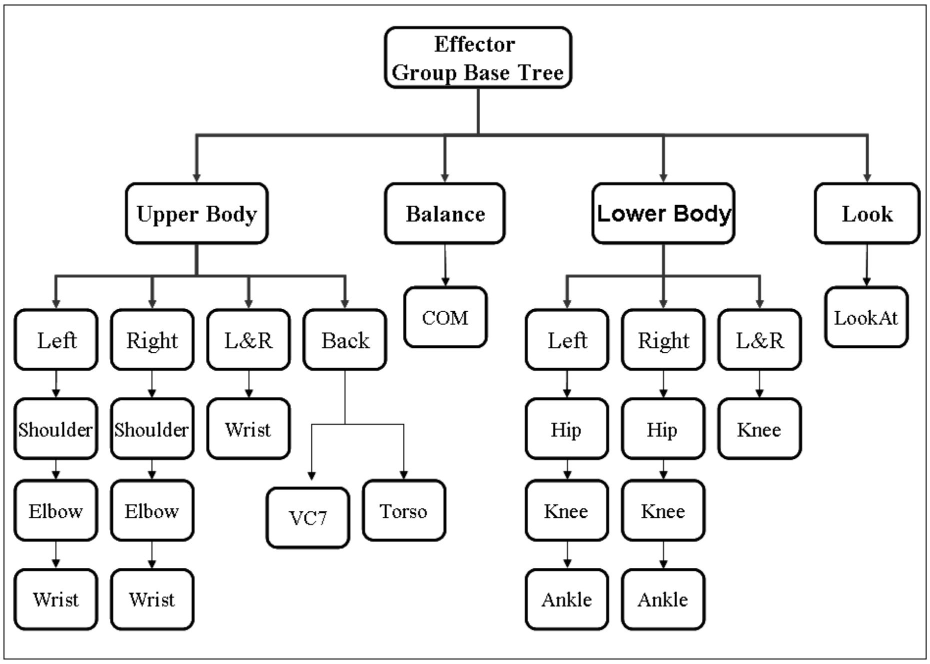


Figure 7.9 Effector Group – Base Tree

The structure of the Effector Group Base Tree is shown in Figure 7.9 and it consists of layered combination of Upper Body, Lower Body, Balance and Look each of which is sub divided in to sub trees. Any joint at particular position in the hierarchy has the following characteristic parameters such as

- Joint Name
- Group Name
- Type
- Priority
- Weight
- Recruiting Level
- Visibility

The range of values of the parameters are listed in the Effector-Characteristic Table for each group layers such as main group, sub group and the effector at the joint level are shown in Table 7.1

name	type	priority	weight	recruitLevel	visibility	group name
pos_l_shoulder	position	0-10	0-10	0-MAX	ON/OFF	grp_l_arm
ori_l_shoulder	orientation	0-10	0-10	0-MAX	ON/OFF	-
pos_r_shoulder	position	0-10	0-10	0-MAX	ON/OFF	grp_r_arm
ori_r_shoulder	orientation	0-10	0-10	0-MAX	ON/OFF	-
pos_l_elbow	position	0-10	0-10	0-MAX	ON/OFF	grp_l_arm
ori_l_elbow	orientation	0-10	0-10	0-MAX	ON/OFF	-
pos_r_elbow	position	0-10	0-10	0-MAX	ON/OFF	grp_r_arm
ori_r_elbow	orientation	0-10	0-10	0-MAX	ON/OFF	-
pos_l_wrist	position	0-10	0-10	0-MAX	ON/OFF	grp_l_arm/grp_lr_arm
ori_l_wrist	orientation	0-10	0-10	0-MAX	ON/OFF	-
pos_r_wrist	position	0-10	0-10	0-MAX	ON/OFF	grp_r_arm/grp_lr_arm
ori_r_wrist	orientation	0-10	0-10	0-MAX	ON/OFF	-
pos_l_hip	position	0-10	0-10	0-MAX	ON/OFF	grp_l_leg
ori_l_hip	orientation	0-10	0-10	0-MAX	ON/OFF	-
pos_r_hip	position	0-10	0-10	0-MAX	ON/OFF	grp_r_leg
ori_r_hip	orientation	0-10	0-10	0-MAX	ON/OFF	-
pos_l_knee	position	0-10	0-10	0-MAX	ON/OFF	grp_l_leg/grp_lr_leg
ori_l_knee	orientation	0-10	0-10	0-MAX	ON/OFF	-
pos_r_knee	position	0-10	0-10	0-MAX	ON/OFF	grp_r_leg/grp_lr_leg
ori_r_knee	orientation	0-10	0-10	0-MAX	ON/OFF	-
pos_l_ankle	position	0-10	0-10	0-MAX	ON/OFF	grp_l_leg
ori_l_ankle	orientation	0-10	0-10	0-MAX	ON/OFF	-
pos_r_ankle	position	0-10	0-10	0-MAX	ON/OFF	grp_r_leg
ori_r_ankle	orientation	0-10	0-10	0-MAX	ON/OFF	-

name	visibility	group name
grp_l_arm	ON/OFF	grp_upper
grp_r_arm	ON/OFF	grp_upper
grp_lr_arm	ON/OFF	grp_upper
grp_back	ON/OFF	grp_lower
grp_l_leg	ON/OFF	grp_lower
grp_r_leg	ON/OFF	grp_lower
grp_lr_leg	ON/OFF	grp_lower

name	visibility	group name
grp_upper	ON/OFF	-
grp_lower	ON/OFF	-
grp_balance	ON/OFF	-
grp_look	ON/OFF	-

Table 7.1 Effector Characteristics Table (Joint Level, Sub-group and main group level)

7.3.3 Control Scheme for Interactive Postural Control

The intuitive manipulation of the articulated systems by minimal interaction with the mouse is achieved by enforcing a control scheme for the grouping of effectors while running the IK-Engine in the back ground.

The Table 7.2 describes the strategy for the control scheme, which gives the priority and weights for the joint involved in the Effector group. Using these Visual effectors user could adjust the humanoid posture simply by dragging joints. The Visual effector object creates the set of effectors by the control scheme when the right mouse button clicks on a valid joint. Dragging the mouse then attempts to move that joint by creating an effector at that selected joint; the dragging only occurs on the plane parallel to the screen. Descending joints are joints that are children of the main joint. Ascendant joints are the main joint's parents up through the root. Other joints are any joints not been given a priority and weight rating. When a joint type is given an n/a rating, it has not been assigned any rating. In this implementation, the main effector will recruit the root joint, except for the "Just One" control scheme where the main effector recruitment level stops just short of the root joint.

Scheme	Main Joint	Descendent	Ascendant	Root	Other
All Simple	medium	n/a	n/a	n/a	low
All Layered	medium	high	low	high	low
Upward Simple	medium	n/a	low	n/a	n/a
Upward Layered	high	n/a	medium	n/a	n/a
Just One	high	n/a	n/a	n/a	n/a

Table 7.2: Control scheme for dynamic effector set up upon mouse click on a valid joint

7.4 Results

7.4.1 Interactive Postural Control

Figure 7.10 shows the wireframe model and the control balls (shown red) are used for intuitive manipulation for the back and knee. By a single push button, IK will be activated and the control balls will be ready for dynamic interaction. Upon clicking the ball, it would turn green and the user could drag it in the control plane. The dimension of the plane is limited to the joint limits of the selected anthropometric model from the population. The control scheme of the visual effectors knee and back are as shown in the table 7.3

Once the posture of the manikin is set up, by selecting reach effectors (left reach or right reach), the control ball would be moved to the wrist. Selecting the ball and dragging would result the dynamic movement of arms and body as a whole depending upon the recruiting level of the joints. The results are shown in Figure 7.10. During the analysis, GUI provides the balancing option also to the user. Depending upon the application, user could select high or low value for the balance, which in turn sets the priority and weight of the Centre of Mass Effector internally. Figure 7.10 shows the result for low and high value set up.

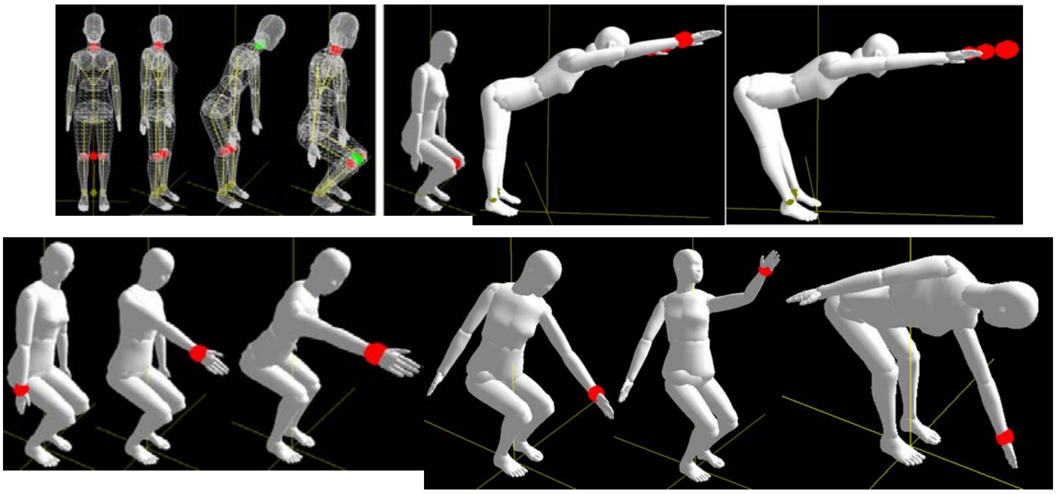


Figure 7.10 intuitive interactive posture manipulation by a simple mouse click on the visual effectors (control balls shown in red and green)

VisualEffectors						
Scheme	Sub Group		Joint	Effector Parameter		
				priority	weight	recruiting level
All Simple	Main	MED	current	7	7.0	10
	Other	LOW	All Joint	1	1.0	10
All Layered	Main	MED3	current	7	7.0	10
	Descendent	HIGH	child	10	10.0	10
	Ascendant	LOW	parent	1	1.0	10
	Root	HIGH	Root	10	10.0	0
	Other	LOW	All Joint	1	1.0	10
Upward Simple	Main	MED3	current	7	7.0	10
	Ascendant	LOW	parent	1	1.0	10
Upward Layered	Main	HIGH	current	10	10.0	10
	Ascendant	MED1	parent	3	3.0	10
Just One	Main	HIGH	current	10	10.0	10

Table 7.3 : Predefined Setup of priority based grouping of effectors4 (priority and weight are grouped as LOW (1,1),MED1(3,3), MED3(7,7) and HIGH (10,10)

7.4.2 Generation of task oriented effector template

The key challenge for the design engineer is to set up the desired initial posture. Figure 7.11 shows the developed user-interface to set up and create the posture template for the desired task. Targeting the non-specialist user of the system, appropriately selecting the radio buttons from left to right in the figure 7.11, the desired initial posture template could be easily set up. Interface has also been provided to select and position each body part separately to fine-tune the initial posture after creating the sample template.

For posture template creation a user is provided with choices, sequentially. User can opt for stand or sit position, may chose for support on either hands of required magnitude with knee bent or straight and any leg in forward or backward position. Based on the template rules generation in this sequence, effector base group tree hierarchy is updated from previous priority setup to the current status resulting into the desired postural template.

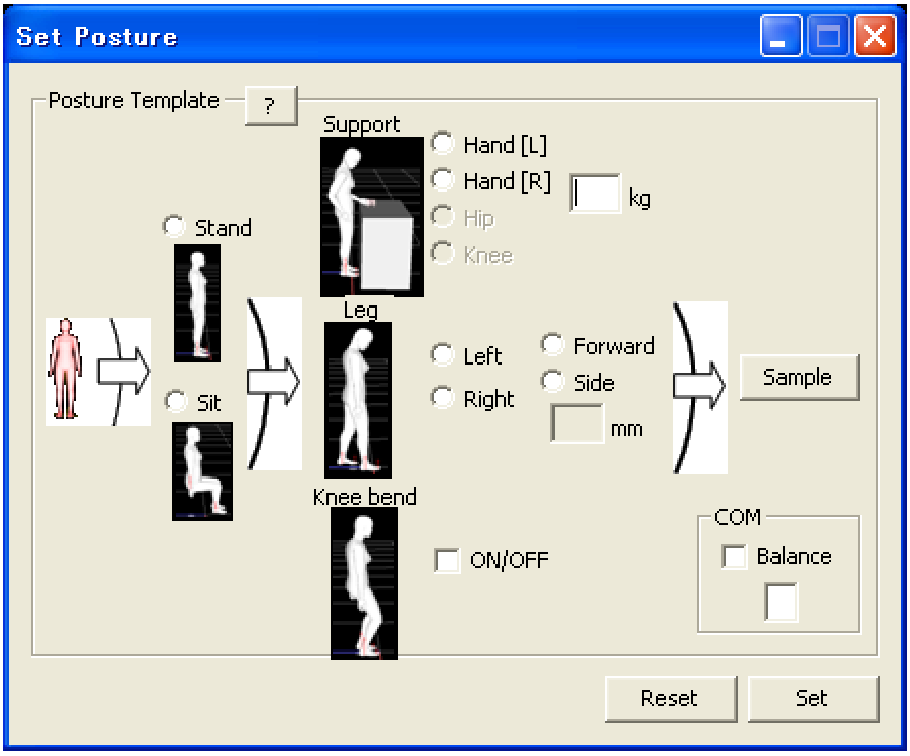


Figure 7.11 Interface for posture template creation

7.4.3 Trajectory Generation for Object Manipulation

Sequential process of trajectory generation for any object manipulation in the virtual space by the digital human is demonstrated in Figure 7.12 and 7.13. A designer can specify the parameters for the trajectory generation through simple mouse click over the sophisticated and interactive GUI in the real time. A general procedure for object manipulation can be carried out in following way.

1. Creation of the digital human (manikin) in the virtual space according to the user

prescribed information.

2. Selection of end Effector, right arm, left arm, leg etc.

3. Selection of the plane for prescribed object manipulation task. For example x-y plane for opening a door.

4. Selecting the transit points for the trajectory.

5. Specifying the magnitude of force on transit points, if needed.

User enjoys freedom to intuitively customize the manipulation strategy in the real time by adjusting, modifying or varying the control points even in a non-sequential manner. Apart from all these features a user can choose to visualize color scheme representing the ease of operation in the manipulation task. Real time graphical representation of torque, MVC values at associated joints along with several other user-friendly features are displayed on the design window simultaneously.

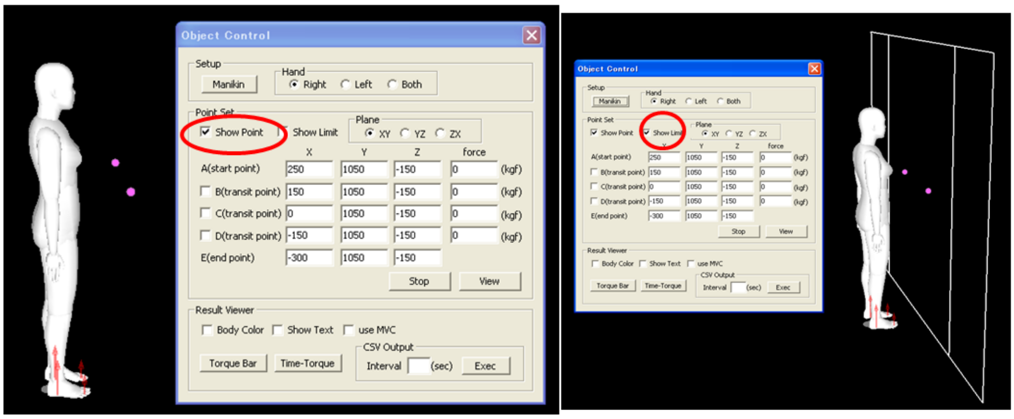


Figure 7.12 Interface for generating trajectory for an end effector

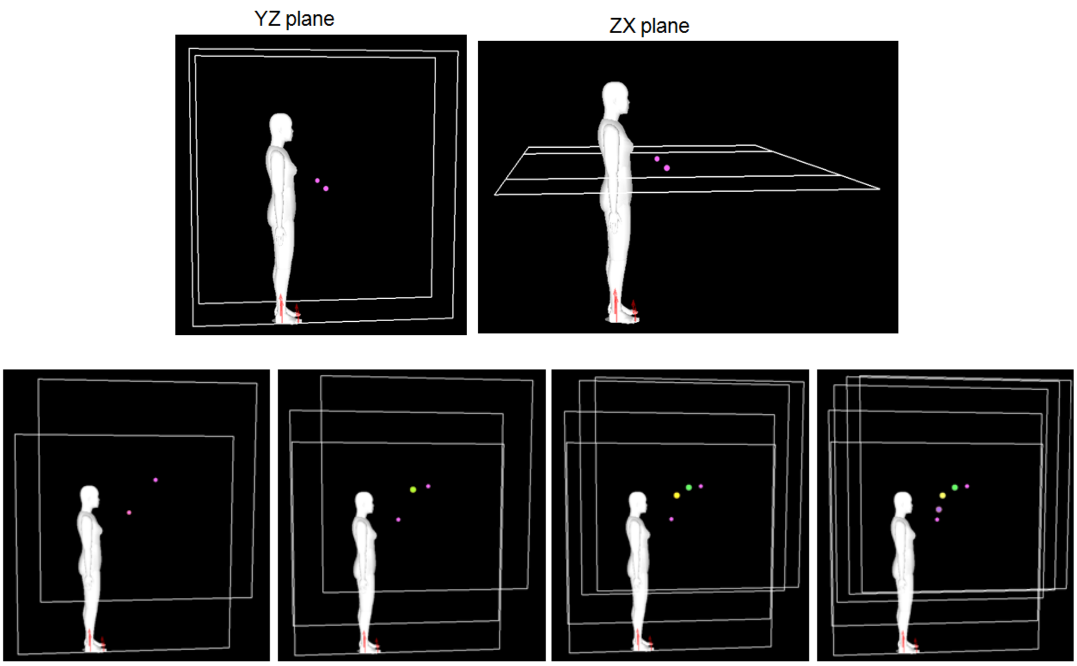


Figure 7.13 setting up of trajectory control points interactively by mouse

7.5 Conclusion

This chapter demonstrated the possibilities and effectiveness of Inverse Kinematics techniques by priority based efficient grouping of the end effectors. By defining a few high level handles, the posture of a virtual human can be driven synergistically for a task such as the reach and object manipulation. For that purpose we exploit Prioritized Inverse Kinematics to define constraints associated with a priority level so that important properties are enforced first (e.g. balance) while less important adjustments are made in the remaining solution space. Using the developed system, user could control anthropometric digital human postures intuitively by interacting with a "Visual Editor" in real time.

Chapter 8
Total System as an Ergonomic Evaluation Engine

8.1 Introduction

To incorporate human factors at the conceptual design stage we intend to replace the traditional 2d drawing/drafting with 3d world, consisting of heterogeneous population of user models. It may seem obvious that the most important two key factors we have to keep in mind are 1) Real-time simulation and 2) Direct on-line interaction of end-users with the system; such that even a non-specialist should be able to use the system through traditional interaction devices like the mouse. Using an intuitive control facility, design engineers should be able to input a simple CAD model, design variables and human factors in to the system. The evaluation engine generates the required simulation in real time by making use of an anthropometric digital human model Database, Physical Characteristic Database and prioritized Inverse Kinematics architecture. Figure 8.1 shows the abstract view of the total system.

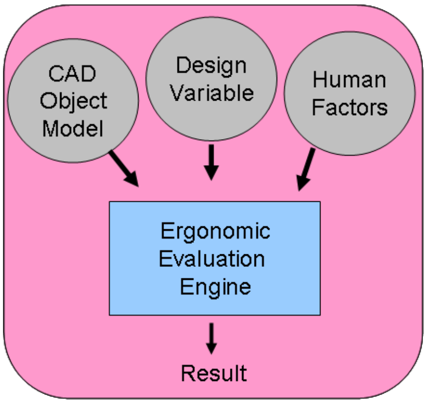


Figure 8.1 Abstract view of the total system as an Evaluation Engine

8.1.1 Key Components and functions

From a designer's view point of conceptual design stage, the necessary data flow of the total process could be briefed as the following

1. Create a simple CAD object model to visualize the conceptual design
2. Set up appropriate design variables
3. Define the target users and set up the required human factors for the analysis
4. Define the required action sequences and set up the analysis scenario
5. Visualize the situation and analyse the result
6. Adjust the variables (design variables and human factors) and repeat step 2 through 5
7. Modify the conceptual design if necessary and repeat the whole process from step 1.
8. Ready for detailed design, possibly with digital and/or physical mock up

The necessary basic building blocks and the key functions that are required to make the developed digital human system as an evaluation engine at the conceptual design stage of a product can be listed as the following

1. **Functions/interfaces to create 3D product model**

   With the available 2D drawings at his disposal designers job is to create 3D object model starting with simple object model using primitive geometries and then combining them as single unit. Additionally designer may need to address the mobility of the part and the axis of rotation of the rotary motion comes into picture.

2. **Interface functions between user model and product model**

   Coupling the user model with the actual intended task to quickly determine how different environmental variables affect ergonomic indices of interest. This layer will enable the designer to set up the objective design variables and to link the digital human with the design.

3. **Assessment functions for ergonomic evaluation**

   Based on the simulation scenario defined by the designer, these functions help communication of the evaluation factors to the system.

4. **Viewer and interface functions**

   The functions developed in this layer would provide the GUI for designer to interact and manipulate the anthropometric data and the conceptual design intuitively.

5. **Result visualization functions**

   Based on the work done in the previous chapters, AVC values for a human with defined physic-demographic is taken as a parametric base for determining the design space. For the visualization of the simulation, AVC values at the desired joint/joints will work as the defining constraint for carrying out the required task which can then be plotted as a contour graph, with design variables as the main axis.

8.2 Design Variables and Human Factors

Design variables are very much dependent on a particular product, and for each design variable the affected human factor also would be different. For example, to define a preferable height of an object, the affecting factors would be different according to the context. If the object is just a holding handle, it is just enough to analyse the permissible height of the handle for the selected population. Whereas if the object is a shelf, the designer has to know a) whether it is reachable b) Is it possible to pick an object from the shelf c) What is the maximum weight a person can pick up from that height d) Is any object placed in that height is visible e) whether people at different ages, differing height could use the shelf for the designed height etc.

Figure 8.2 gives an overview of the design variables in the context of this research

Figure 8.2 Design Variable examples in the context of this work

In the case of house hold items, each product has its own functionality and the design variables vary from product to product providing a wider designing space resulting into multiple permutation and combinations of the processes. Whereas in the case of automobile, air craft or clothing industry, the design variables are already known as the product is already defined and the designing space is limited by the preset requirements (door handle, position of seat-belt, driver seat etc.),.
As shown in Figure 8.2, some examples of the design variables can be listed as

1. Sink depth
2. Bath tub height
3. Bath tub Handle position
4. Pull down shelf
5. Position of down shelf in the kitchen
6. kitchen counter and height of the sub height
7. depth of refrigerator
8. height of the washing machine
9. Positioning of switches in a room
10. Door handle etc.

In that scenario, to incorporate human factors to plan house-hold products, it is highly necessary for the designer to be provided with basic functionalities to define the design variables in an easy way. Accordingly, we aim at coming up with a generic strategy to define the variables that could be linked with virtual humans.

Towards the development of Generic Engine, the strategy and the method to develop the user-defined input variables such as CAD Object models, design variables and Human factors are described as shown in Table 8.1. The design variables are classified mainly in to two categories namely primary variables and secondary variables. Human factors are broadly classified in to action, posture and anthropometry and age. Results will be evaluated using the human performance measure which could be physical limits, joint torques and perception.

Object Design Variable			Human Factors			Performance Measure
	Primary	Secondary	Action	Posture	Anthropometry	
Single	Height Width Depth Weight Trajectory Location	Pick up an Item Keep an Item Translate Rotate Slide	Reach Push Pull Open Close Step Up	Initial Final Hand position Leg position Stand Sit Half Sit	Position Age Sex Height Weight Arm Length Balance	Joint Torque Perception Energy
Multi	Height & Height Height & Width Height & Depth Width & Depth	Move an Item From A ->B				

Table 8.1 Strategy table to categorize the design variables and Human factors

8.2.1 Simple CAD Object Model Creation

Simple models could be created with either primitive geometries or with predefined templates. In the case of simple models with boxes and spheres, functional components have been developed to merge each individual component to combination unit.

Figure 8.3 shows the two approaches of creating the simple 3D model from 1) 2d drawing 2) 2D images/Photo.
In the case of approach 1, interfaces have been developed where the user can input 2D sketches as bit-map images. The images should include front view, side view and top view. In the second approach, texture mapping functions are being developed such that simple 3D model of the existing product can be visualized as such. The bases of these methods are depending on a template database of different products that have been developed.

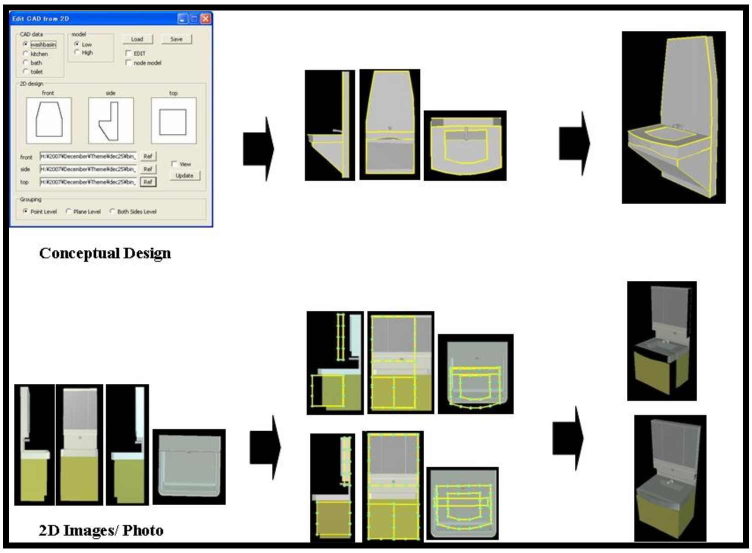


Figure 8.3 3D model creations from a conceptual design / 2D images and photos

8.2.2 Pre-defined templates with variable functionalities

The developed templates are simple and editable for products like wash basin, kitchen, bath tub and toilet as shown in the figure 8.5, so that designer could directly select the appropriate model for the evaluation process. There are two types of template models: Low polygon model and high polygon model. An intuitive interface to edit this templates also being made so that even a naïve user can edit the model using simple mouse operation

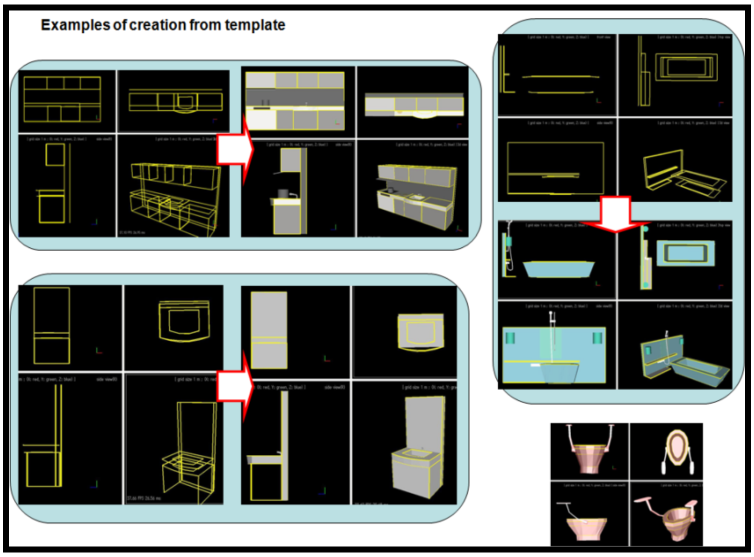


Figure 8.5 Pre-defined templates with for washbasin, kitchen, bathtub and toilet.

Upon selecting the CAD object template, user could select any part to be edited, using mouse and modification can be made in point level, plane level and also as a unit level, by appropriately selecting the desired criteria. Figure 8.6 depicts the intuitive, interactive designing using the predefined templates with an example of kitchen model

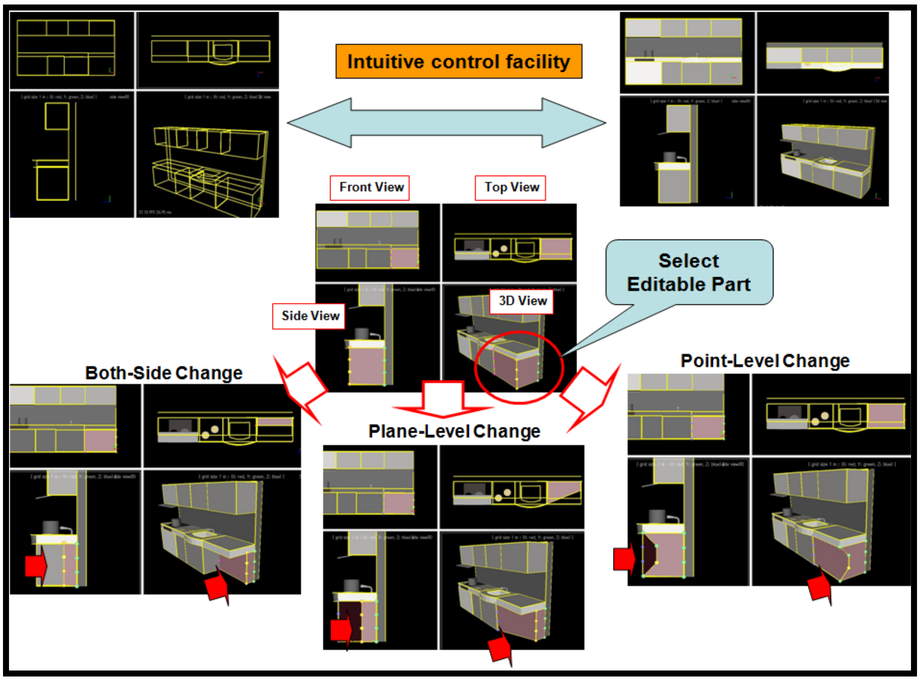


Figure 8.6 Intuitive design controls with easily editable interfaces

8.2.3 Interface functions to set up evaluation factors

To set up the evaluation factors user has to define the primary variables and secondary variables. Accordingly Simulation Engine should be informed what is to be evaluated. For example, if we define the primary variable as width of a counter, the simulation engine should know what should be the reference of COM (centre of mass) of the selected object. Accordingly an easy-to- use interface has been developed such that user could set the direction using arrow marks as shown in figure 8.7.

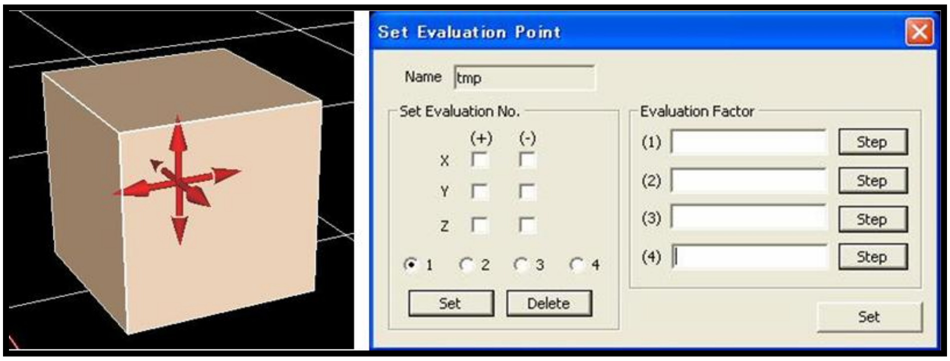


Figure 8.7 Interface functions to set up evaluation factors

Similarly while creating the simple CAD object model; user can set the axis of rotation of the object intuitively such that the created object could be used as door (push/pull or slide), window or any other desirable objects as shown in Figure 8.8

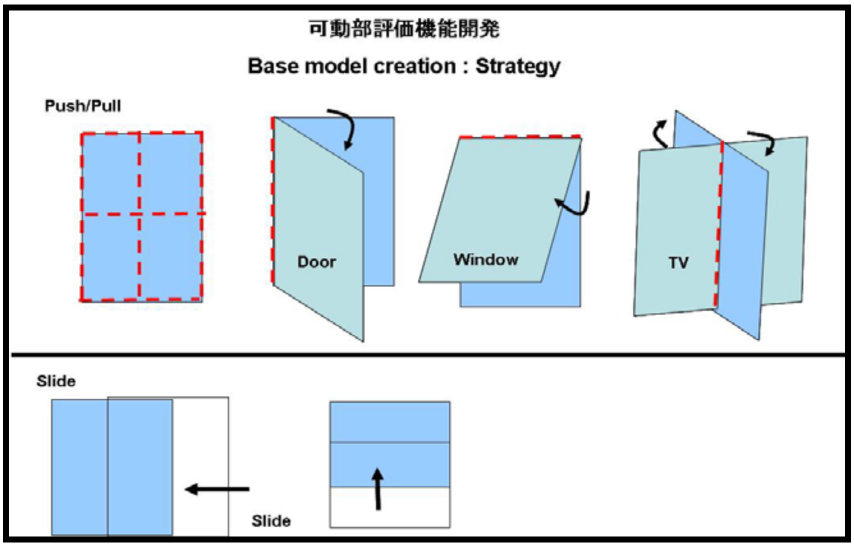


Figure 8.8 Strategy to link User-Model with Design Variables

8.2.4 Coupling functions between User-Model and CAD object

To link user-model with design variable, we have created generic interface functions to move an object with digital humans and to set up a trajectory for the moving objects. Couple of snapshots of the results is shown in Figure 8.9 and Figure 8.10. In the first case, the digital human is trying to rotate a TV and in the second case, the task is to set up the trajectory of a pull down shelf visually. Designers can interactively specify the trajectory of a moving object by moving the control points (dots shown in the figure) using a simple mouse click. Using the developed generic trajectory set up interface, designer has the freedom to select their desired design object and the associated joint trajectory to be visualized. Figure 8.11 shows the couple of other scenario; first case being sliding door analysis and the second one, a bath tub height analysis. Designers enjoy interactive specification of the trajectory by moving control points and the effort generated by the user can be monitored in the real time. Depending on the height of the bath tub, the end-effector trajectory for the leg can be automatically set up through interactive specification of the variables.

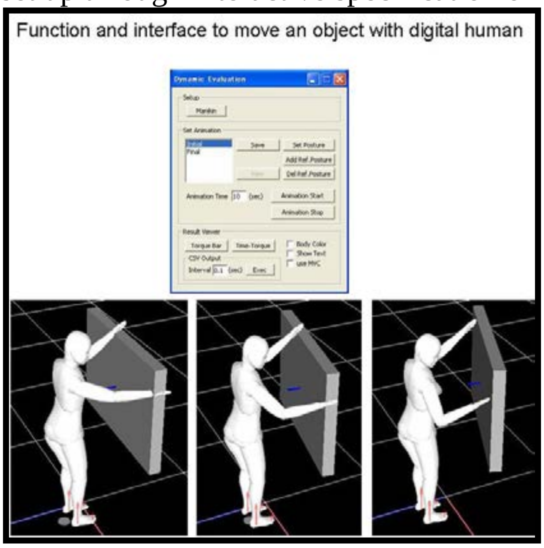


Figure 8.9 Example snapshot (Interface between user-model and Object)

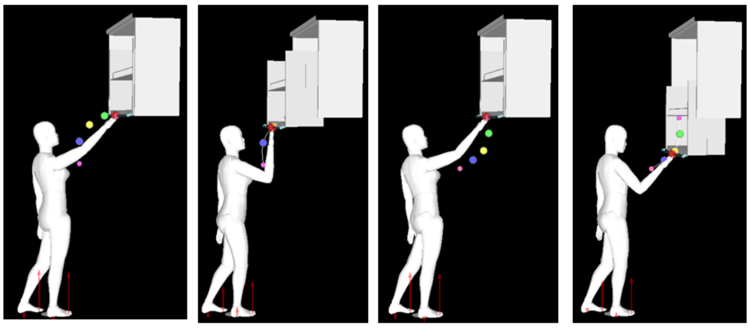


Figure 8.10 Interactive method of setting up the trajectory of a pull-down shelf.

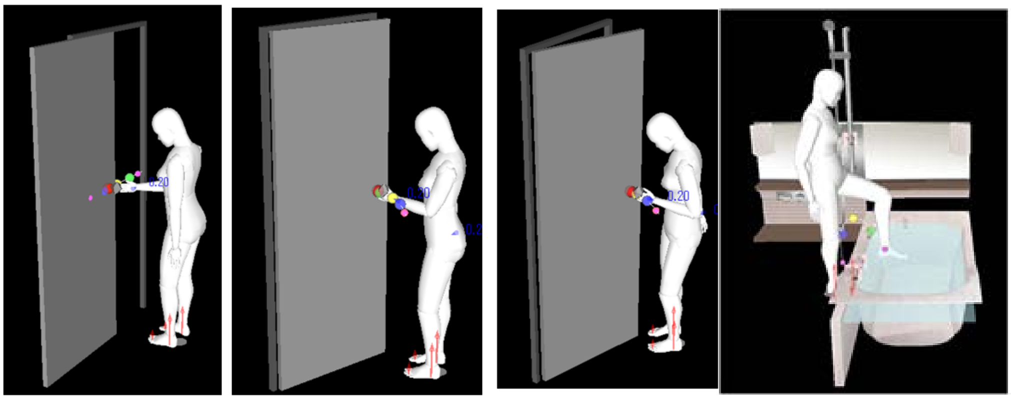


Figure 8.11 Snapshots for door slide, open, close; and Bath –tub height evaluation

8.2.5 Simultaneous Visualization of Different View points

Figure 8.12 displays a snap shot from the simulator showing the reach action in front of a kitchen by a child and adult and the eye-view of the both virtual human can be simultaneously seen as shown in the top-left and top-right images

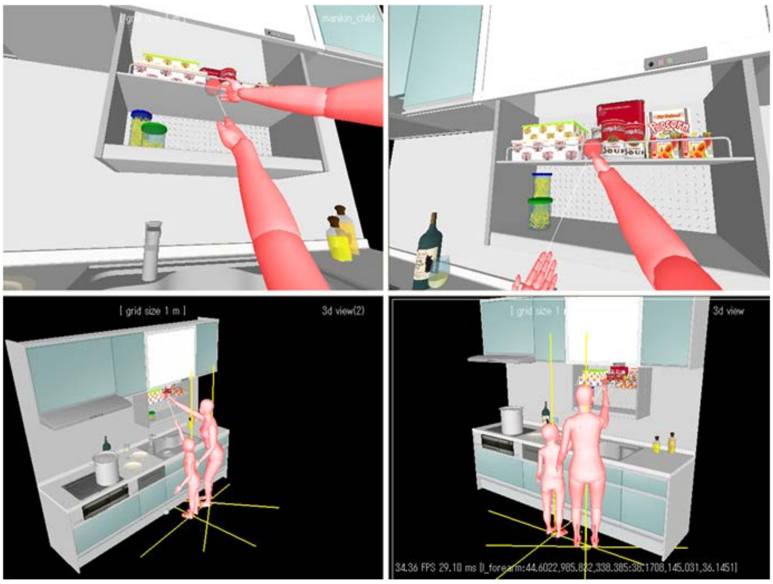


Figure 8.12: The reach action in front of a kitchen (by a child and adult)

8.2.6 Result Visualization Functions

Functions have been developed to visualize the simulation result as a contour graph, such that the designers could easily visualize the permissible range of values of the target design variables. In most of the cases, Affordable Voluntary Contraction (AVC) could work as the parametric base for drawing the counters in the graph. There might be cases where AVC is not relevant too (For example to determine the permissible width of a wash-basin counter such that a human would not collide with the mirror in front of the wash-basin, while doing a *wash action*, the parametric base for drawing the contour in the graph would be *distance of head of the digital human with the mirror*!)
The interfaces being developed is based on a general approach, giving the designer the complete freedom of control to choose the desired variables to be assigned for each axis. All the simulation data has been saved as a CSV file. Upon selecting and setting up the axis values, the system will produce the contour graphs as shown in figure 8.13 and 8.14. The contours are coloured automatically based on the threshold set by the user, green and yellow showing the permissible zone while the zones showing the gradation of colours from yellow to red are the one to be discarded, while going for the next design stage of the product (That is while moving up from conceptual design stage to detailed design and physical mock up).

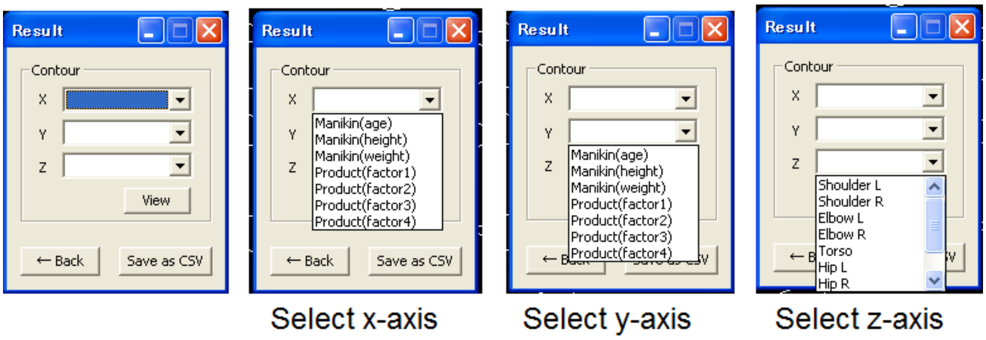


Figure 8.13: Interfaces to plot the contour graph

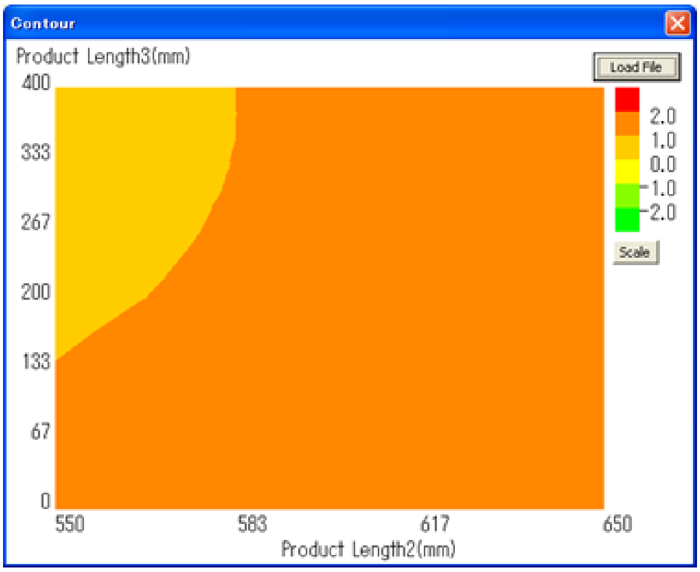


Figure 8.14: Contour Visualization

8.3 Functional Assessment of the Simulation Software

8.3.1 Validation based on the feedback from actual human subjects

A mock-up of the wash basin has been made and their monitor evaluation (41 people having height range from 135 cm to 190 cm) were carried out by changing the counter height from 70 cm to 95 cm and asking each monitor about the comfortable minimum height of the counter while making a wash action. The digital human simulations were also being carried out with similar anthropometric models of the monitors and the torques exerted by digital humans is compared with the decision values of real humans. The dark line in the graph in Figure 8.15 shows the decision made by the digital humans and the green line shows the one made by real subjects.

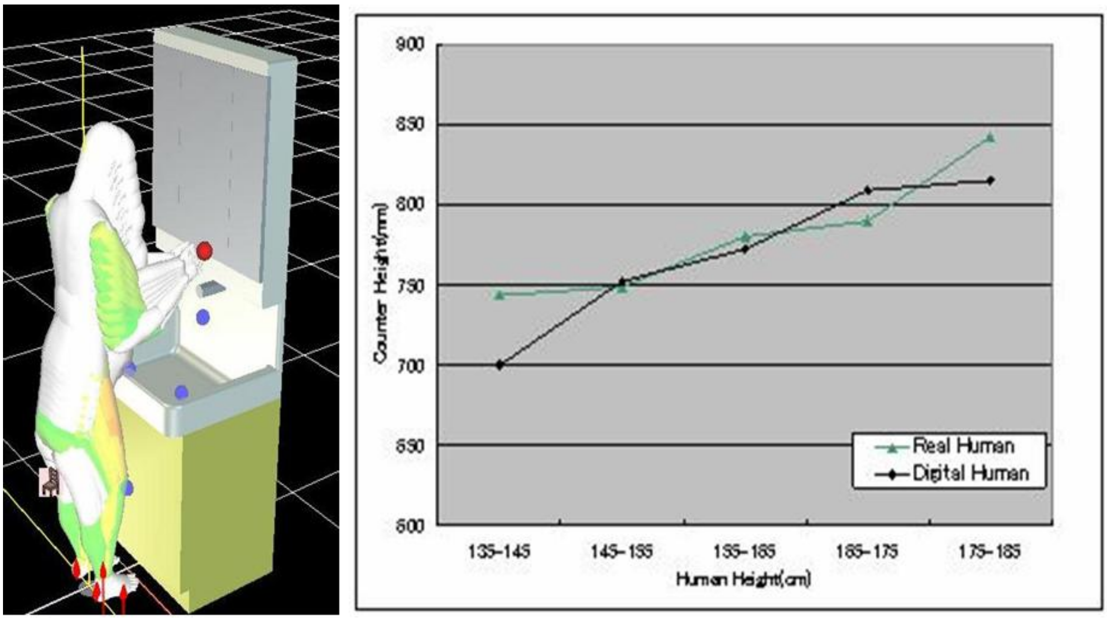


Figure 8.15 Validation of the simulation by comparing the results with real-human subjects

The results of digital human simulation and the feedback from the subjects clearly indicate that the developed digital human simulation can be used as an evaluation tool at the conceptual design stage.

8.3.2. Trajectory – Analysis of Pull down Shelf (with External load)

It includes the validation by analyzing the trajectory of a pull-down shelf by comparing the EMG values of monitor and shoulder torque of digital humans. Posture analysis for the biomechanical accuracy has been explained in chapter 4, which included only the static posture analysis at a pre-defined control points. Here we exploit the whole motion of the pull down shelf and comparison of EMG with torque for the whole trajectory.

The focused application is a pull-down shelf of a kitchen. The constraints for the design criteria were defined as the following.

1. The height of the handle of the shelf should be reached by a person with a minimum height of 1.5 M
2. While pulling down the shelf, user of all ages should be able to do the action with least effort

3. The weight of the shelf, while pulling down, should be adjusted automatically such that "the user" is not frightened when the shelf comes towards the user.

Using diverse anthropometric digital humans, the simulation is being generated. The torque exerted at each joint are estimated and compared with the corresponding MVC and AVC values. It is found that the diagonal trajectory is the optimal solution for a wide range of population.

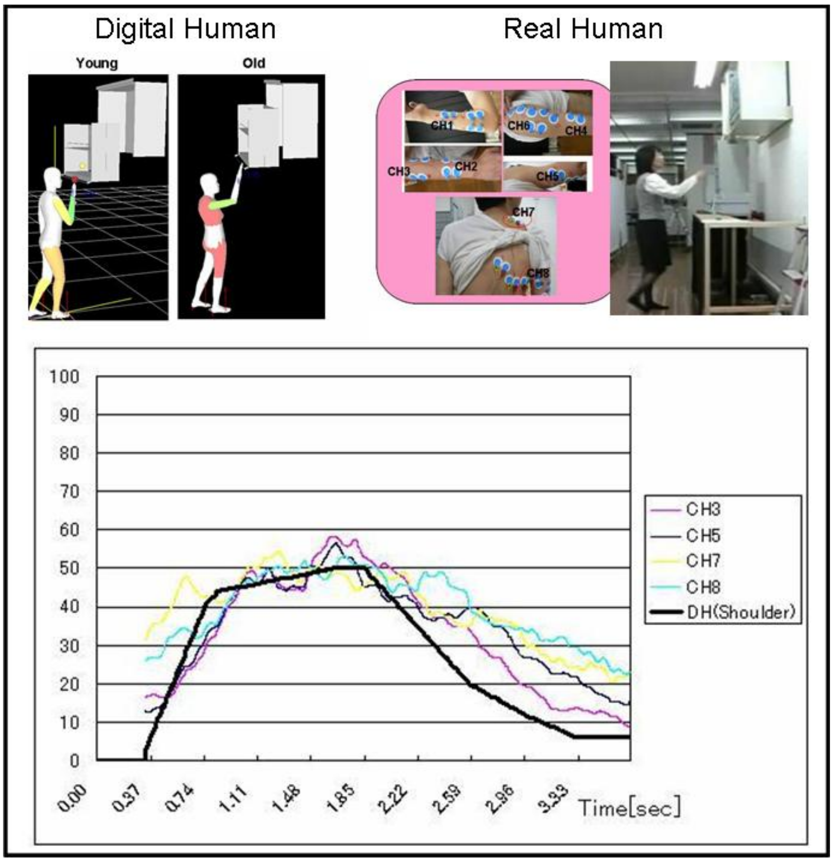


Figure 8.16 Validation of the simulation by comparing the results with real-human subjects (Pull-down Shelf)

To validate the result, a few subjects were asked to perform the action of push up and pull down of shelf with right hand and EMG analysis were carried out. The digital human of each subjects are also being made with equivalent age, height, waist and arm length and the simulation is being carried out with the same weight input for the pull-down shelf. The diagram 8.16 shows the comparison of normalized values of digital human torque (dark line) exerted at the right shoulder with EMG cumulative average of (selected monitor) channels 3, 5, 7, and 8 for the push up action.

The results of the functional assessments clearly indicate that the developed digital human simulation can be used as an evaluation tool at the conceptual design stage.

Inference and limitations

From the designers view point, points of interests are

- Initial posture, final posture, flexibility and strength. Unfortunately, IK does not guarantee the desired final posture as it has many large solution space. As shown in Figure 8.17, it is possible to have different posture configuration for the pull down shelf. So we have to come with supporting interfaces to let the designer set the final posture also, by providing key frame animation.

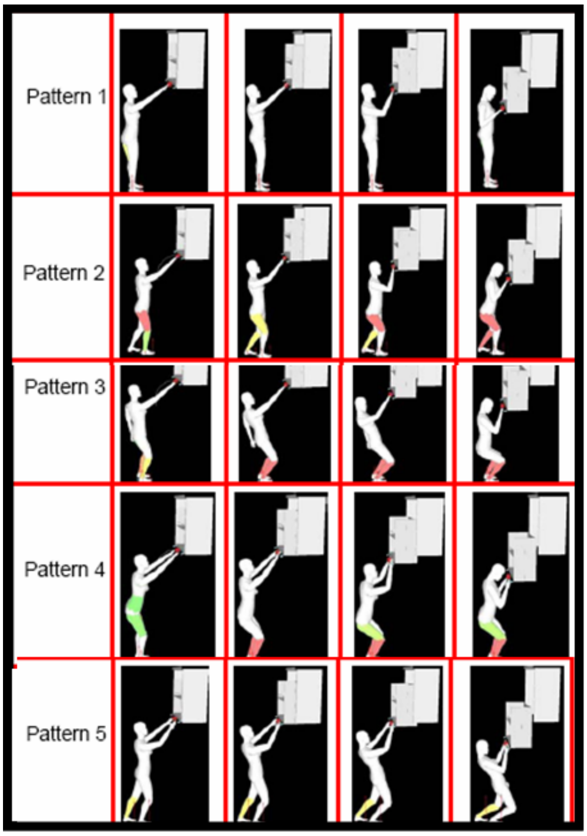


Figure 8.17 Example of different posture patterns for a single action – Pull-down Shelf

Section E

Results & Conclusion

Chapter 9
Results and Conclusion

"Designing all products, buildings, and exterior spaces to be usable by all people to the greatest extent possible"- The concept of Universal design is becoming ever more important as the ageing population is increasing. Engineering design is, in the midst of a paradigm shift from *fitting the human to the system to fitting the system to the human*, prompting designers to incorporate anthropometry and age factors in their product designs. This dissertation introduced an Ergonomic Simulator for Universal Design applications at the very conceptual design stage of product development cycle. This chapter concludes the dissertation by discussing a couple of case studies to understand the usage and advantage of the developed system as an ergonomic evaluation engine.

9.1 Discussion of the results with examples

9.1.1 Counter depth and Sub-counter Height Estimation of Kitchen

The goal of the simulation was to determine the approximate range of values for the counter width and sub-counter height of a kitchen, such that the system is affordable by a heterogeneous population with differing abilities. The step by step method to set up the simulation scenario is explained below.

1. Simple Kitchen Model Creation Using Primitive Geometry Model

This stage includes creation of the simple kitchen models i.e. counter, sub-counter and combining these into a unit using the GUI provided to the designer. The user can create multiple simple objects and combine them with desired dimensions as shown in Figure 9.1

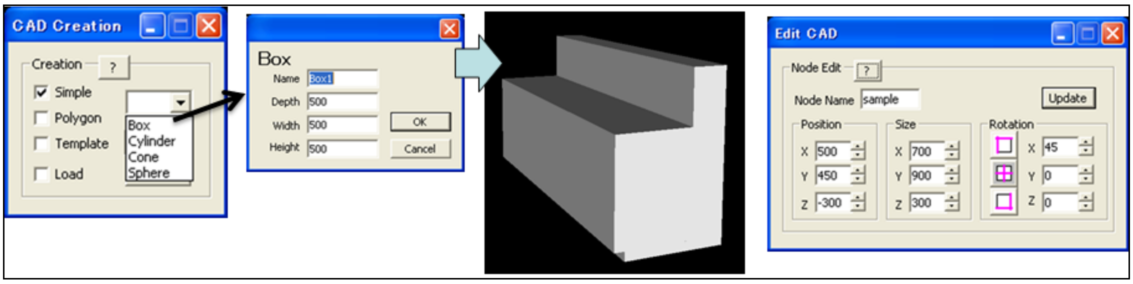


Figure 9.1 setting up of the CAD object as a kitchen sample model using GUI

2. Set up the Design Variables

Based on the strategy described in previous chapter, the design variables are classified in to two types and they are primary variables and secondary variables. In the present scenario, the primary variables are the combination of Counter width and sub-counter height. The secondary variables can be defined as moving an object of specified weight from main counter to the sub-counter. The strategy to help the designer to set up these design variables are developed as shown in Figure 9.2 The desired task is to move an object of specified weight from position C to A, for which the best fit combination of counter depth and sub-counter height is optimally selected from the range of these primary variables.

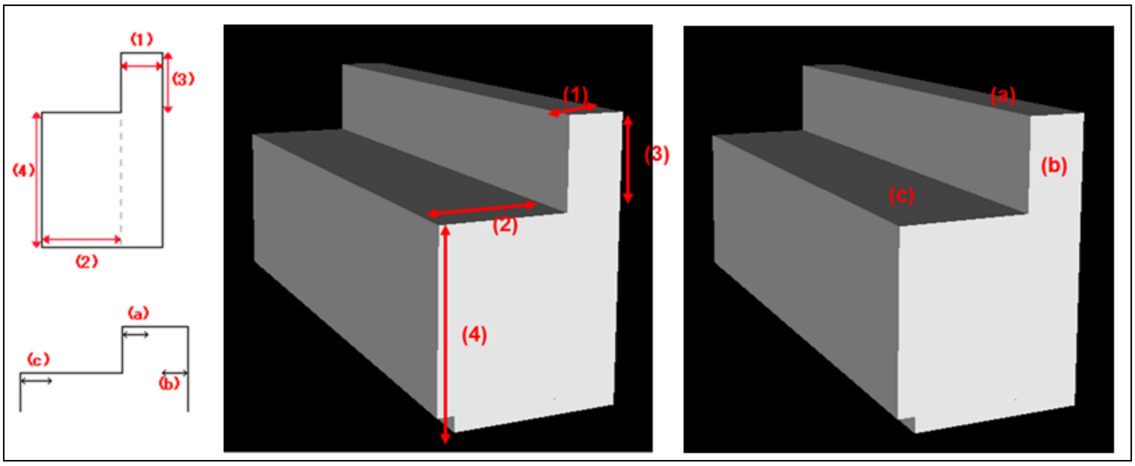


Figure 9.2 Primary and Secondary Design Variables

3. Define the Target Users and Set up the required human factors for analysis

The range of primary variables will be different for carrying out a defined task for target user having various physic-demographic profiles containing range of height, weight and the respective age groups. So determining factor for the primary variables is governed by the defined task type and the physic-demographic profile of a user.
In the case of this simulation scenario the target users can be easily defined by the user. An example could be the following

Human Factors
Target User
Height : 1.4m ～1.8 m
Weight: 50 kg ～ 70 kg
Age: 30 ～ 70
These values can be set through the provided GUI as shown in Figure 9.3

4. Set up the Evaluation Factors and Simulation Scenario

.
As shown in Figure 9.3, the designer is provided with the GUI, having evaluation factors (primary design variables) are numbered as 1, 2, 3 and 4 corresponding to the height and width of the counter and sub-counter. Secondary design variables are defined to be “moving an object from counter to sub-counter” (shown the location a, b and c in figure 9.3) User can specify the location of initial and final position of the object as a function of the edge of the counter. User can also input the weight of the object through the GUI. Regarding the human factors, GUI has option to input the height, age and gender of the virtual human. Initial posture, action (with one hand or both hands) and the desired trajectory of the object motion also can be set up easily through the GUI.

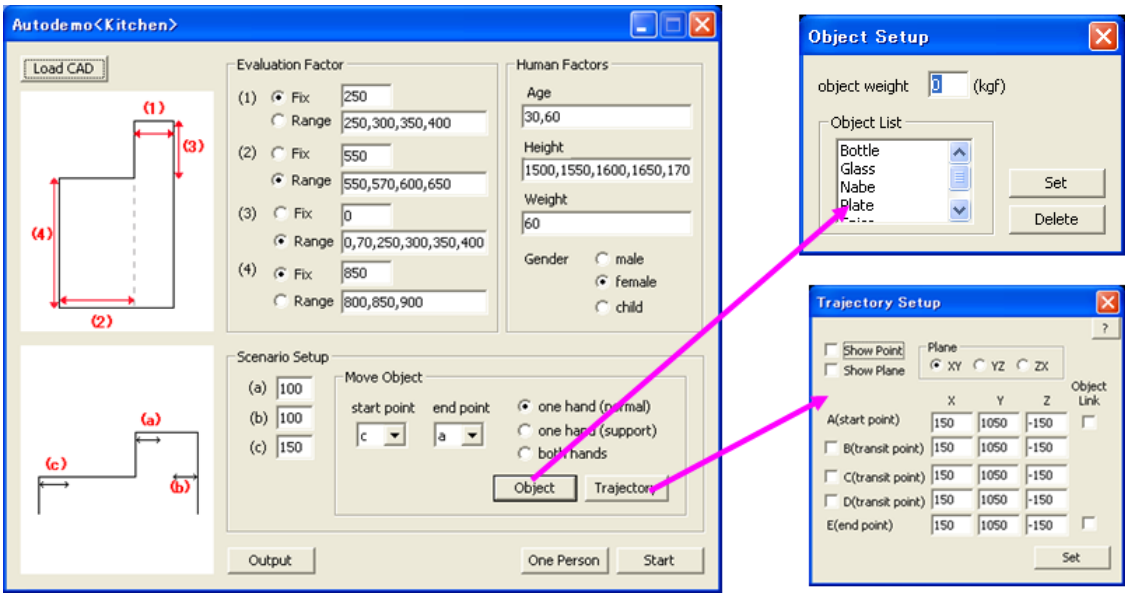


Figure 9.3 Interface for setting up the simulation scenario

The evaluation factors can be defined as either fixed value or range of values for the desired combination of (1), (2), (3) and (4) as shown in figure 9.3. The location of the position (a), (b) and (c) can also be easily set up through the GUI as a function of the distance of the location from the counter. Using the object set up interface, the moving object weight and the type can be defined. User is also given the freedom of choosing the action as action with one hand, action with one hand with the other hand being supported or the action with both hands. The trajectory of object motion from C to A can also be interactively set up with the Sub-Gui provided, including the intermediary control points from the source to the target destination.

5. Visualize the Simulation and analyse the result

After completing the scenario-set up, a click on the start button in the GUI would start the simulation in real time. As per the values assigned through GUI, CAD model will automatically change during each simulation step and so does the trajectory as shown in Figure 9.4. The snapshot of the simulation is shown in Figure 9.5. The corresponding results (torque values for each joint for each digital human for each combination of counter-width and sub-counter height) are saved as a CSV file which could be loaded in to a desired contour graph (Figure 9.5) by properly defining the axis.

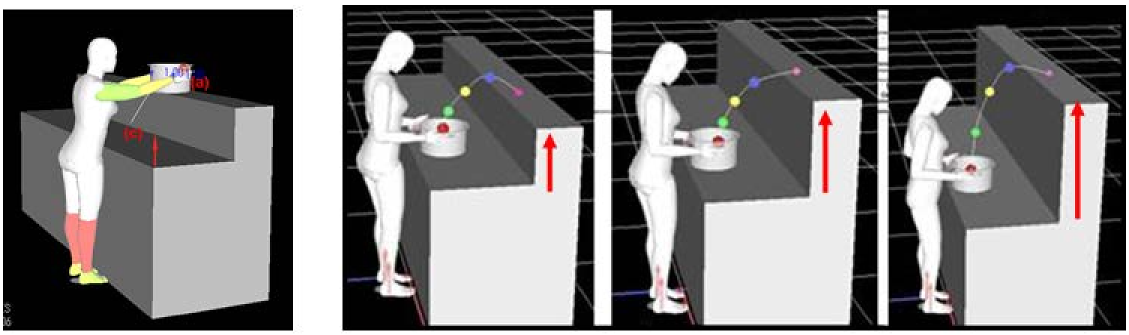


Figure 9.4 Assessment functions example images

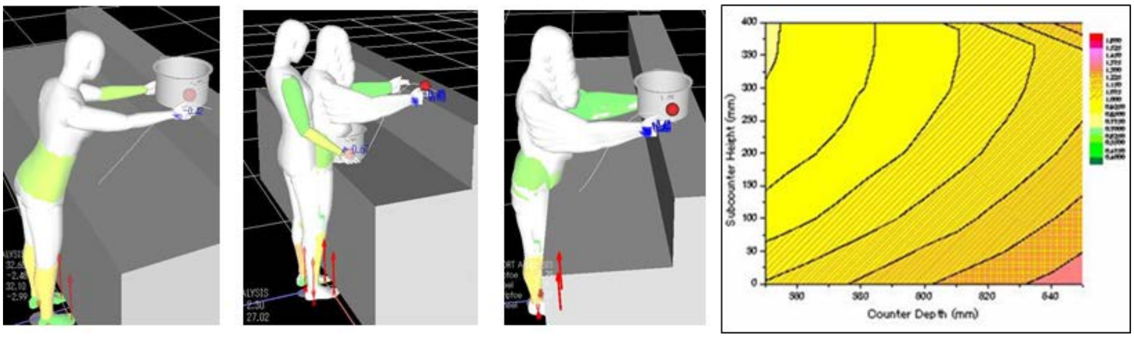


Figure 9.5 Simulation Visualization

Based on the work done in the previous chapters, AVC values for a human with defined physic-demographic is taken as a parametric base for determining the design space. For the visualization of the simulation AVC of a user will work as the defining constraint for carrying out the required task, of moving an object from (c) to (a). Torque generated by the joint during the task of defined parameters (counter depth, sub-counter height, trajectory of moving the object) will be compared with the MVC value in real time. The threshold of torque generated within which the user can easily carry out the task without any exertion felt is represented in green colour. As the required torque for the desired task increases above this threshold approaching the MVC is gradually represented from medium (orange) to difficult and strenuous (red). Counter depth and sub-counter height are plotted on a graph and the contours of this graph represent zones of ease (green and yellow), gradual build-up of strain (orange) and reaching to the difficult zone (red) in a gradually increasing manner. With this interactive zoning a designer can easily figure out his range of option in designing the variables for counter depth and sub-counter height, where the orange and red contours would be avoided.

Using different anthropometric digital humans, simulation is being carried out. The torque exerted at each joint are estimated and compared with the corresponding MVC and AVC. Optimal range of values for counter width and sub-counter heights can be successfully estimated. The contour graphs [Figure 9.5] shows the affordable values with green and yellow.

9.1.2 Permissible height of the drop-down shelf

The aim of the case study is to determine the permissible height of the drop-down shelf of a kitchen for a whole population of human ranging from different height groups. During a general task on the counter beneath the drop down shelf, the user's head should not collide with the shelf. Based on the distance between the user's head and the drop down shelf the contours of designing space has been defined as permissible to restricted zones (from green to red) with the reduction in the gap between the head and the shelf. The simulation scenario is pictorially shown in Figure 9.6. The digital human is asked to perform any task near the sink while the shelf is moving down.

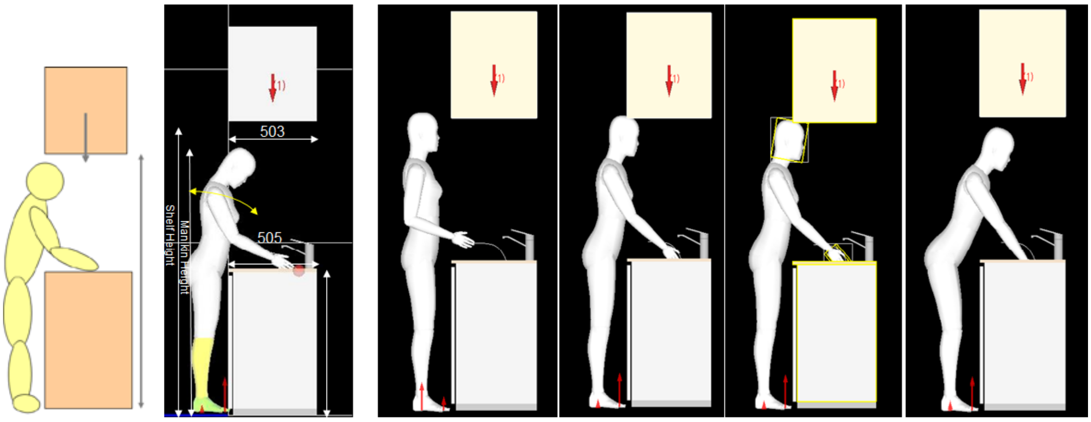


Figure 9.6 Simulation of drop-down shelf

A number of combination for the two factors were analysed and the permissible designing space is determined in gradually changing zones of ease from green to red. It is found that by considering the maximum height of 95 percentile of Japanese women, the height of the drop down shelf installation should not be lesser then the 1.72 M and the results are pictorially shown in Figure 9.7

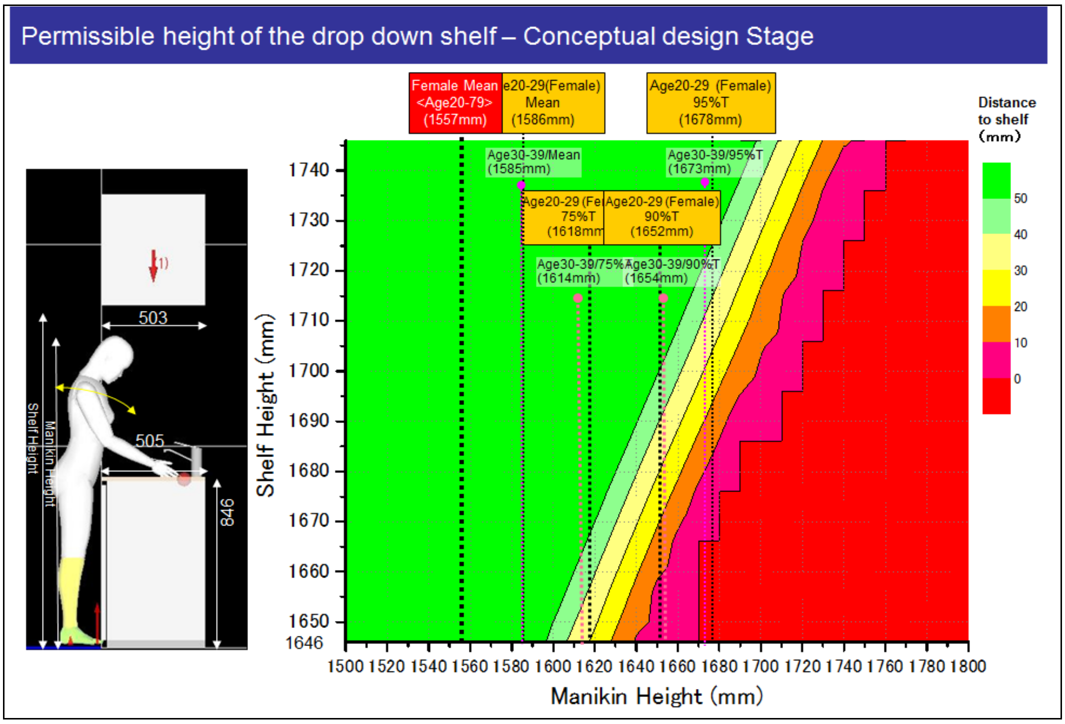


Figure 9.7 Simulation result visualization of drop-down shelf, the color coding based on the distance between head-top with height of the shelf

9.1.3 Couple of snapshots from different simulations using the developed system

Figure 9.8 displays snapshots of Real-Time simulations of different anthropometric models and the bar-graph attached under corresponding scenario shows the torque value experienced by the digital user model of diverse profiles at each joint.

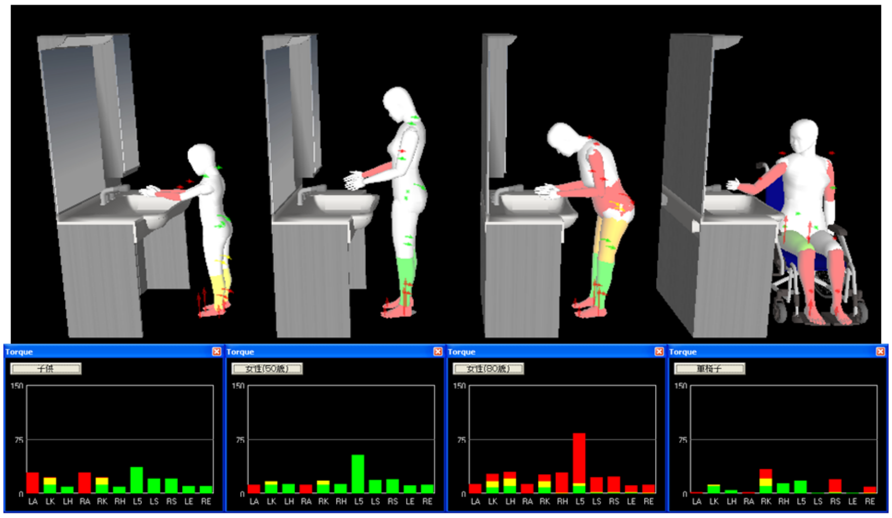


Figure 9.8 Real-Time simulations and corresponding torque values of different anthropometric models in front of wash basin

Figure 9.9 some snapshots demonstrating the usage of the developed system as an ergonomic tool.

Figure 9.9 depicts some snapshots of the digital human model of diverse profiles carrying out different activities to demonstrate the usage of the developed system as an ergonomic tool at the conceptual design stages of various products. By modifying and updating concerned specifications interactively the developed system performs numerous activities and the responses are simultaneously measured in the real time.

9.2 Conclusion

A broad platform by which a non-specialist user can experiment with and manipulate anthropometric data intuitively in real time has been developed and the potential usage of the system as an ergonomic evaluation engine for the conceptual design stage of a product design has been demonstrated with examples.

Abstract overview of the developed system architecture is summarized in figure 9.10. User interface layer integrates the user with the simulation system, where user can be a designer or a consumer. For a designer the system will act as an ergonomic design tool while for a consumer it functions as a decision making tool. System interface layer connects the simulated virtual human with the virtual world.

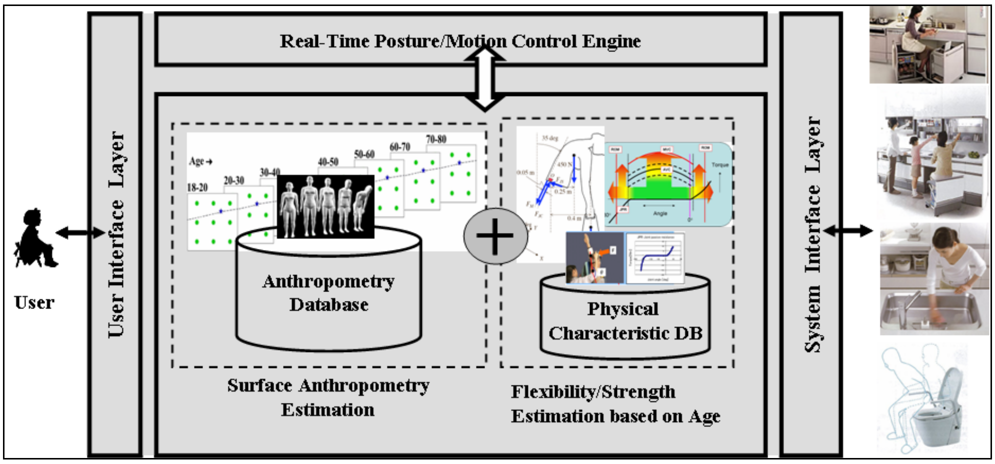


Figure 9.10: Overview of the total system architecture

User interface layer provides for a graphical interface for the interaction of the user with the simulation system. Interface layer for the user consists of generation of user model, CAD object model, camera view orientations and creation of functions for scenario assessment, to name a few. Core of the simulation system consists of modules for creating body, strength and motion control of virtual humans.

Using an intuitive control facility, design engineers can input a simple CAD model, design variables and human factors in to the system. The evaluation engine generates the required simulation in real time by making use of an anthropometric digital human model Database, Physical Characteristic Database and prioritized Inverse Kinematics architecture. The proposed system could be an efficient tool for helping designers for easier and earlier identification of ergonomic flaws. The results are validated with real human subjects indicating the practical implication of the total system as an ergonomic design tool. A complementary direction of the present research is to create a decision-making tool that enables customers to more easily evaluate existing products, and as a promotional tool to demonstrate the effectiveness of a new designs.

9.2.1 Contribution

A complete framework for ergonomic simulation at the conceptual design stage of a product development cycle based on parametric virtual humans in a prioritized inverse kinematics framework while taking biomechanical knowledge into account has been introduced. The project concludes by making two *original contributions as well as a number of sub-contributions:*

Contribution 1:

Includes an ageing algorithm for anthropometric digital human models

We introduced a quantitative approach to strength estimation for a whole population by making use of a physical characteristic database of actual human subjects. Our research will be complementary to those prior investigations but distinguished from them by adding an ageing module as the key factor. Our approach is empirical and our models derive directly from data.

Contribution 2:

Provides a broad platform by which a non-specialist user can experiment with and manipulate anthropometric data intuitively in real-time

Traditionally, articulated biomechanical models are the province of specialists. This fact alone inherently limits the usefulness of such tools to testing large, expensive, pre-existing designs despite their great potential as design tools. This limitation is compounded by the large amount of time that such tools require to return useful feedback. By providing intuitive manipulation and creation of the models, non-specialists can begin applying their own branches of expertise to put these tools to new purposes altogether. Rather than testing a few existing designs, all types of new designs can be created and experimented with. By providing instantaneous feedback that responds dynamically to a user's input, the tool ceases to operate as a means of testing designs and becomes a tool for discovering new and revolutionary designs that might not have even been imagined otherwise. As such, the effect of the contribution is not merely quantitatively superior, but qualitatively novel and innovative.

Sub-contributions:

- Coupling of DHM with CAD (Generic method/techniques for task planning and setting up the design variables.)
- Replacing of 2D drawing/drafting with 3D world
- Real-time Intuitive interactive control for the whole population for reach, step up and object manipulation tasks
- Estimation of Affordable Voluntary Contraction (AVC) for different age groups
- Total system as a generic ergonomic evaluation engine for the conceptual design stage
- A decision making tool that enables customers to more easily evaluate existing products
- Promotional tool to demonstrate the effectiveness of new designs

9.3 Limitations & Challenges

The availability of data limits the scope and reach of the project in at least three important ways. First, data for flexibility and strength was not adequately available for each year represented in the population and had to be represented as ten year groups. Similarly, Affordable Voluntary Contraction measurements were by necessity overly conservative since data was not available for each age group. As a result, minimum percentage thresholds of comfort were taken for the entire population and applied to each age group's maximum voluntary contraction measurements. Moreover, no such data was available for children in the population and was thus not included in the program.

Motion control techniques had to be kept as simples as possible in order to maintain a responsive real-time environment and accommodate the available data. While inverse dynamic techniques more easily include functionalities such as tracking fatigue generated by extended activities, pseudo-static algorithms with inverse kinematics techniques were used since they were more computationally efficient. Since inverse kinematics techniques produce large solution spaces for a digital human's final positions after performing a scenario, time-intensive key frame animations must sometimes be used. To keep models useful as design tools, they had to be easily programmable and responsive in a real-time environment. To this end, the detail achieved in a full digital mock-up had to be reduced and the number of joints minimized.

9.4 Future directions

Recognizing our responsibility as researchers, our aim is development of the society and the well-being of the people and specially caters to the needs of the ever increasing number of aged people, by inventing new techniques and providing a platform for innovative application building up thereby enhancing the quality of life throughout the world. To bring this broad goal into reality a three-pronged approach is required.

Symphonizing Technology by combining existing technologies with the novel emerging technologies, generation of new benefits that we could not achieve with conventional systems.

Symphonizing comfortable functions by integrating and controlling individual functions of each facility with new technologies, creating new ways to use space and maximize comfort.

Symphonizing spatial design by harmonizing standards of each element composing space with their design taste, creating not just the combination of the facilities but high quality living space tailored to the taste of whole population.

Conceptualizing this futuristic society with enhanced freedom and comfort encompasses catering to the safety and security of the user and his harmonious relationship with the ecological factors for sustainable future.

Our research work intended to provide a ***test-bed*** for the designers at the conceptual level of the design to create products in making this futuristic society a reality. Our developed model of a digital human works as a foundation over which the viability and efficiency of a design can be tested in real-time.

Planned revisit of the ergonomic simulation is aimed to provide a complete framework in the physical ergonomic domain for conceptual design stage of the product development cycle. The strategy envisaged development of a comprehensive platform based on three basic determinants representing body, motion and application. Ideally the body can be understood to have physical, physiological and psychological factors, while motion may consist of basic stand/sit/reach, walk/run and motion combination. Application can be categorized into three levels: components, system and Living space. In our research focus body model is limited to physical aspects, motion is restricted to sit, stand and reach postures, and application is limited to components. At the conceptual stage, we were more interested in evaluating the strength and flexibility at different ages with interactive, intuitive real time postural control.

Pinnacle of the future scope will ultimately result in realizing an ideal comfortable living space by simulating a virtual environment with the desired parameters of daily life such as optimum value of light illumination, temperature, air flow, living space, equipment location etc. To cognitively experience this virtual environmental set-up, future digital human models need to possess the capabilities of sensing, unrestricted motion and a *near real human body type*. Towards realization of this concept cutting edge research in the areas such as artificial intelligence, sensors and transducers, kinematics, dynamics, autonomous agent behavior, conversational agents and crowd modeling needs is required. Ultimately these all aim to enable a virtual human to variously generate, simulate, visualize, analyze, substitute for and understand human performance.

The *tree-diagram* shown in figure 9.11 succinctly explains the future direction of our work and provides a window to understand the prospective scope of research. Future scope of the research can be divided into three branches as body, motion and application. We have germinated a sapling which can be cultivated into a blooming flower by integrating the existing and emerging technologies in the area of data processing, computer graphics, and physiological, psychological, psychosocial and cognitive studies of human behavior as well as impact biomechanics (for simulating the safety of any design).

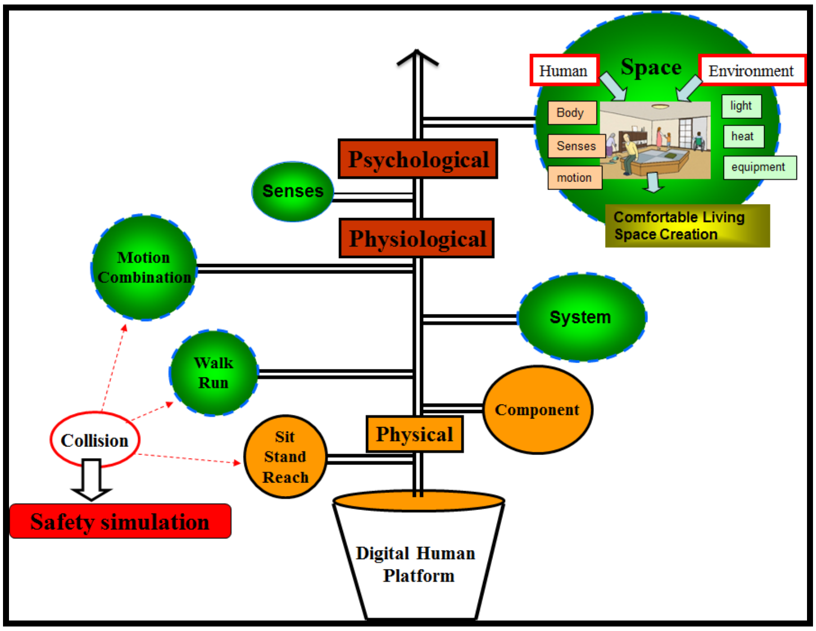


Figure 9.11: Envisaged Future Direction of the research

The immediate future direction (limiting to physical aspects) on the basis of work done on three layers namely, body, motion and application might include following challenges.

- How the aging will impact the postural variation of virtual human.
- By replacing inverse kinematics techniques with inverse dynamic techniques, new types of data can be produced from modeling different tasks. Energy consumption and fatigue, for example, can be quickly determined after each change made at the design stage.
- By adding walking/running and other motion combinations, application scope can be expanded to a larger extent.
- With advances in processing power, the number of joints in the model can be increased without decreasing responsiveness.
- By using recently available surface anthropometry of the children, ergonomic evaluation can be made more universal, if the physical characteristics database (flexibility/strength) is developed in future. Similarly the research scope would further address the needs of differently abled persons and pregnant women.

The safety of a design could be another interesting future direction. Impact biomechanics including Head Injury Criteria (HIC) has been widely used in crash test, especially in automobile industry. Recent trends in emphasizing the need for safe products and environments including the safety of the children and aged people in manual material handling; prompting designers and engineers to come up with tools to identify hazard even at the conceptual design stage of a product. By developing and incorporating impact biomechanics and product characteristics such as stiffness of the material, sharp edge etc., the scope of the ergonomic evaluation tool can be extended to Safety evaluation tool!

Appendix A
HQL Anthropometric Database of 34,000 Japanese people

Appendix A-1
Population Sample distribution based on age

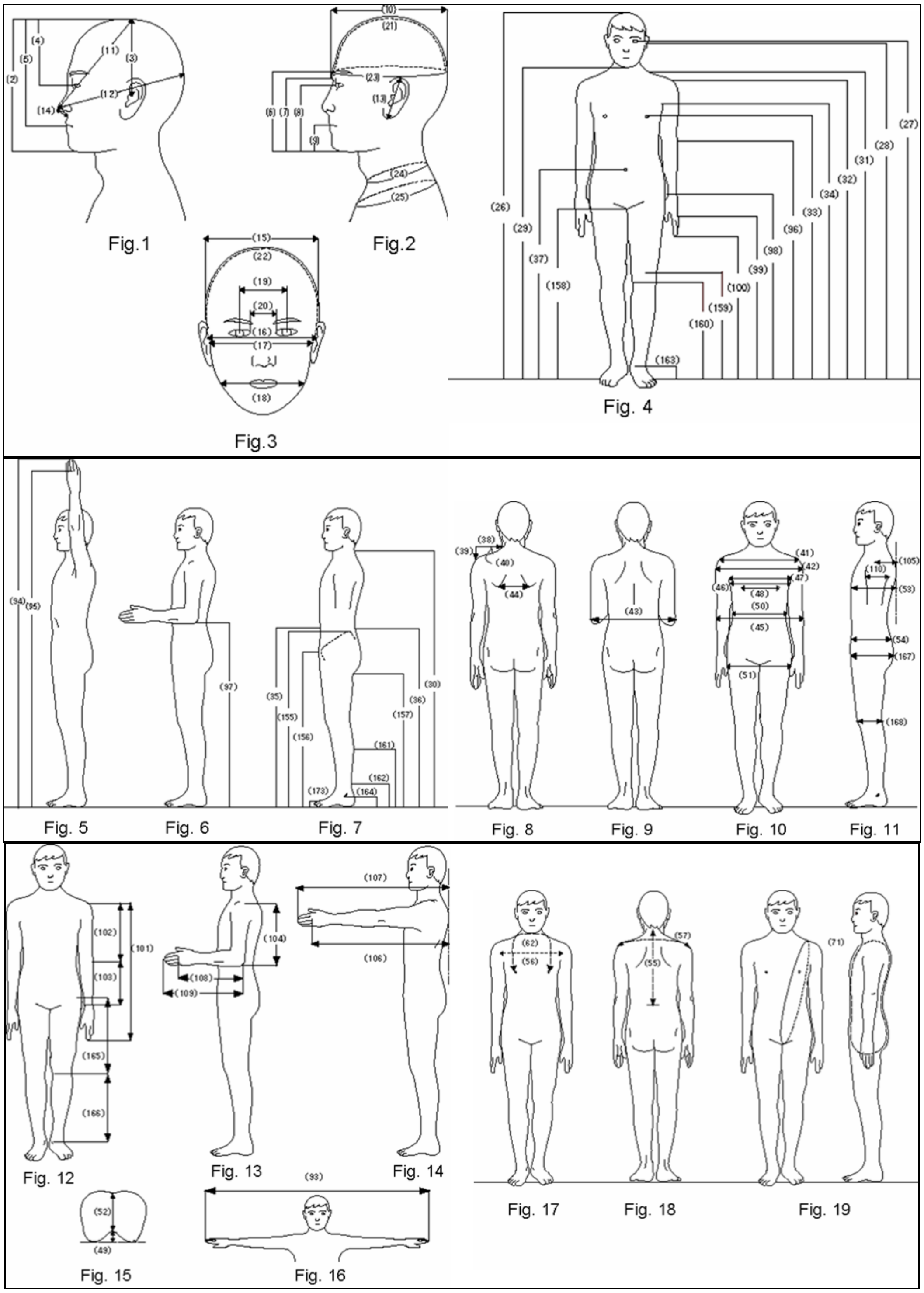
Number of People

Age	Male	Female	Total
0	0	0	0
1	0	0	0
2	0	0	0
3	0	0	0
4	0	0	0
5	0	0	0
6	44	52	96
7	191	219	410
8	369	274	643
9	475	426	901
10	427	355	782
11	482	392	874
12	403	289	692
13	536	342	878
14	496	314	810
15	362	301	663
16	907	734	1641
17	862	776	1638
18	586	610	1196
19	545	1168	1713
20	501	1029	1530
21	343	585	928
22	389	579	968
23	411	415	826
24	490	310	800
25	578	297	875
26	564	242	806
27	488	204	692
28	444	163	607
29	461	132	593
30	403	130	533
31	356	85	441
32	301	113	414
33	280	103	383

Age	Male	Female	Total
34	274	110	384
35	276	107	383
36	237	113	350
37	256	79	335
38	249	92	341
39	203	90	293
40	219	89	308
41	204	109	313
42	262	117	379
43	250	103	353
44	279	109	388
45	248	109	357
46	244	99	343
47	162	86	248
48	190	77	267
49	195	86	281
50	206	102	308
51	194	121	315
52	196	113	309
53	175	111	286
54	137	108	245
55	133	95	228
56	142	100	242
57	118	99	217
58	85	88	173
59	69	104	173
60	51	52	103
61	31	49	80
62	38	68	106
63	28	69	97
64	18	50	68
65	51	66	117
66	48	81	129
67	50	83	133

Age	Male	Female	Total
68	70	81	151
69	68	90	158
70	44	73	117
71	59	89	148
72	55	69	124
73	61	92	153
74	53	72	125
75	43	53	96
76	44	59	103
77	40	71	111
78	47	51	98
79	48	45	93
80	38	37	75
81	29	26	55
82	32	27	59
83	27	16	43
84	16	17	33
85	12	11	23
86	8	8	16
87	11	3	14
88	3	3	6
89	2	2	4
90	6	2	8
91	2	0	2
92	1	2	3
93	0	2	2
94	0	0	0
95	0	0	0
96	2	0	2
97	1	0	1
98			
99			
	19034	14774	33808

Appendix A-2
Measurement Items in the Anthropometric Database



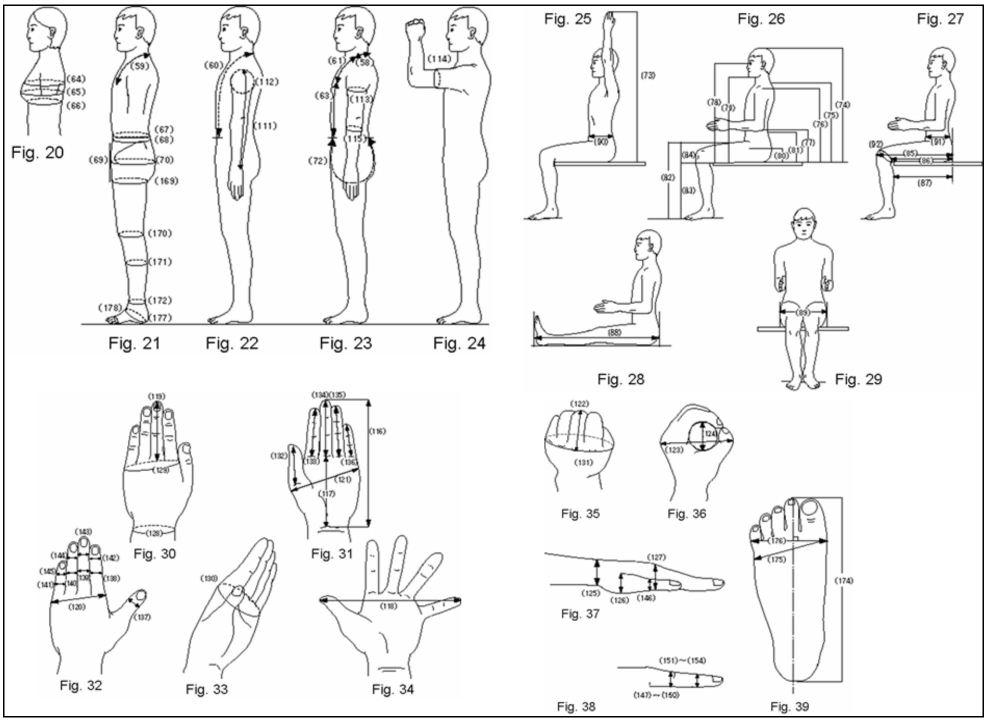


Fig. 20 Fig. 21 Fig. 22 Fig. 23 Fig. 24 Fig. 25 Fig. 26 Fig. 27 Fig. 28 Fig. 29 Fig. 30 Fig. 31 Fig. 32 Fig. 33 Fig. 34 Fig. 35 Fig. 36 Fig. 37 Fig. 38 Fig. 39

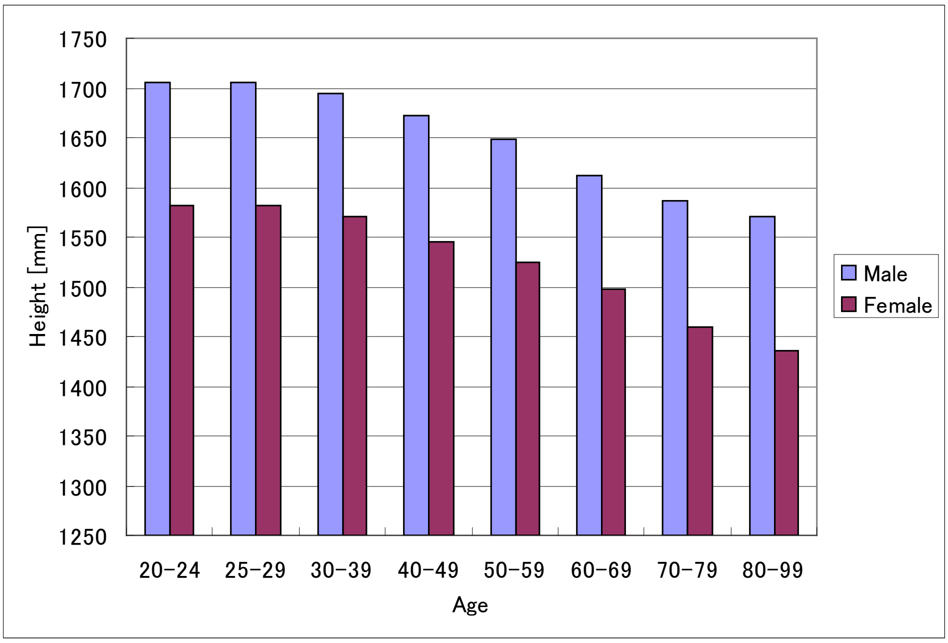
No	Item	Fig	No	Item	Fig
1	Body Weight		41	Shoulder Breadth	7
2	Total Head Height	1	42	Bideltoid Breadth	7
3	Vertex-Tragion Height	1	43	Elbow -to- Elbow Breadth	15
4	Vertex-Pupil Height	1	44	Infeior Biscapular Breadth	14
5	Stomion-Vertex Height	1	45	Maximum Body Breadth	7
6	Glabella-Gnathion Height	2	46	Chest Breadth	7
7	Morphologic Face Height	2	47	Anterior Biaxillary Breadth	7
8	Eye-Chin Height	2	48	Bimammillary Distance	7
9	Stomion-Gnathion Height	2	49	Breast Depth(Only Female)	9
10	Head Length	2	50	Waist Breadth	7
11	Pronasale-Vertex Distance	1	51	Hip Breadth	7
12	Pronasal-Opistocranion Distance	1	52	Chest Depth	9
13	Ear Lengtht	2	53	Maximum Chest Depth	6
14	Nasal Depth	1	54	Maximum Abdominal Depth	6
15	Head Breadth	3	55	Cervical-to-Posterior Waist Len.	14
16	Bitragion Breadth	3	56	Antero-superior Chest Arc	16
17	Bizygomatic Breadth	3	57	Posterior Biacromial Arc	14
18	Bigonial Breadth	3	58	Cervicale -to- Side Neck Length	13
19	Interpupillary Breadth	3	59	Cervical -to- Mammilla Length	11
20	Biocular Breadth	3	60	Cervical-to-Anterior Waist Len.	12
21	Sagittal Head Arc	2	61	Side Neck-to Mammilla Length	13
22	Bitragion Coronal Arc	3	62	Mammilla-to-Mam.Suspender Length	16
23	Head Circumference	2	63	Mammilla-to-Anterior Waist Dist.	13
24	Neck Girth	2	64	Upper Chest Circumference	8
25	Neck Root Girth	2	65	Bust Girth	8
26	Height	5	66	Lower Chest Circum. (Female)	8
27	Eye Height	5	67	Waist Girth	11
28	Tragion Height	5	68	Abdominal Circumference	11
29	Chin Height	5	69	Maximum Hip Girth	11
30	Cervical Height	6	70	Hip Girth	11
31	Side Neck Height	5	71	Vertical Trunk Girth	12
32	Acromial Height	5	72	Total Crotch Length	13
33	Nipple Height	5	73	Middle Finger-tip Hi. Over Head,sitting	22
34	Axillary Height	5	74	Sitting Height	20
35	Front Waist Height	6	75	Opistocranion Height, sitting	20
36	Back Waist Height	6	76	Cervical Height, sitting	20
37	Navel Height	5	77	Acromial Height, sitting	20
38	Side Neck-to-Acromion H. Distance	14	78	Pupil Height, sitting	20
39	Side Neck-to-Acromion V. Distance	14	79	Gnation Height, sitting	20
40	Shoulder Angle	14	80	Waist Height, sitting	20

No	Item	Fig
81	Elbow Height, sitting	20
82	Thigh Height,sitting	20
83	Sitting Surface Height	20
84	Thigh Clearance	20
85	Buttock-Knee Length, sitting	21
86	Buttock-Popliteal Length, sitting	21
87	Buttock-Calf Length, sitting	21
88	Buttock-Sole Length, sitting	24
89	Hip Breadth, sitting	23
90	Abdominal Depth with arms over head	22
91	Abdominal Depth with horizontal forearms	21
92	Knee Girth, sitting	21
93	Arm Span	10
94	Middle Finger-Tip Height over head	4
95	Metacarpal Head Height over head	4
96	Radiale Height	5
97	Elbow Height	17
98	Radial Stylion Height	5
99	Metacarpal Head Height	5
100	Finger-Tip Height	5
101	Upper Limb Length	16
102	Upper Arm Length	16
103	Forearm Length	16
104	Shoulder-Elbow Length	17
105	Acromion-to-Back Distance	6
106	Metacarpal Head from Back Distance	19
107	Arm Reach from Back	19
108	Metacarpal Head-to-Elbow Distance	17
109	Fingertip-Elbow Distance	17
110	Armscye Width	6
111	Sleeve Inseam-to-Wrist Length	12
112	Armscye Girth	12
113	Upper Arm Circumference	13
114	Flexd Upper Arm Circumference	18
115	Forearm Circumference	13
116	Hand Length	26
117	Palm Length	26
118	Finger Span	29
119	Fingertip-to-Metacarpal Head Distance	25
120	Hand Breadth	27
121	Maximum Hand Breadth	26
122	Grip Phalanx Length	30
123	Maximum Grip Diameter	31
124	Inside Grip Diameter	31
125	Wrist Thickness	32
126	Thenar-Pad Hand Thickness	32
127	Hand Thickness	32
128	Wrist Circumference	25
129	Hand Circumference1	25
130	Hand Circumference 2	28

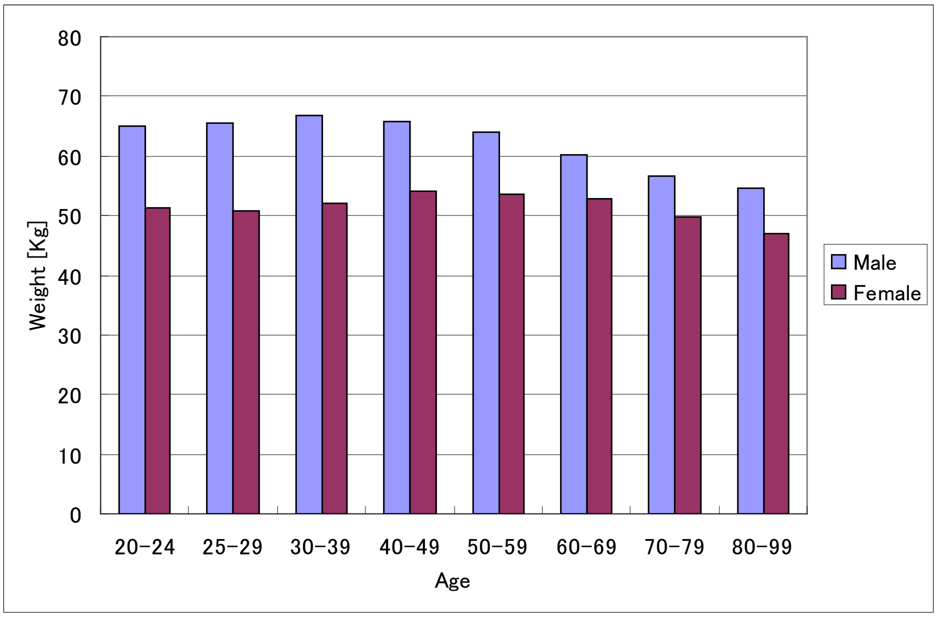
No	Item	Fig
131	Fist Girth	30
132	Finger 1 Length	26
133	Finger 2 Length	26
134	Finger 3 Length	26
135	Finger 4 Length	26
136	Finger 5 Length	26
137	Finger 1 Joint Breadth	27
138	Finger 2 Proximal Joint Breadth	27
139	Finger 3 Proximal Joint Breadth	27
140	Finger 4 Proximal Joint Breadth	27
141	Finger 5 proximal Joint Breadth	27
142	Finger 2 Distal Joint Breadth	27
143	Finger 3 Distal Joint Breadth	27
144	Finger 4 Distal Joint Breadth	27
145	Finger 5 Distal Joint Breadth	27
146	Finger 1 Joint Thickness	32
147	Finger 2 Proximal Joint Thickness	33
148	Finger 3 Proximal Joint Thickness	33
149	Finger 4 Proximal Joint Thickness	33
150	Finger 5 Proximal Joint Thickness	33
151	Finger 2 Distal Joint Thickness	33
152	Finger 3 Distal Joint Thickness	33
153	Finger 4 Distal Joint Thickness	33
154	Finger 5 Distal Joint Thickness	33
155	Lliocristal Height	6
156	Lliospinal Height	6
157	Gluteal Furrow Height	6
158	Crotch Height	5
159	Mid-Patellar Height	5
160	Knee Height	5
161	Calf Height	6
162	Ankle Height	6
163	Sphyrion Height	5
164	Fibular Sphyrion Height	6
165	Thigh Length	16
166	Lower Leg Length	16
167	Hip Depth	6
168	Knee Depth	6
169	Thigh Circumference	11
170	Knee Circumference	11
171	Calf Circumference	11
172	Minimum Leg Circumference	11
173	Foot Thickness	6
174	Foot Length	34
175	Foot Breadth	34
176	Projected Foot Breadth	34
177	Oblique Ankle Girth	11
178	Foot Circumference	11

Appendix A-3:

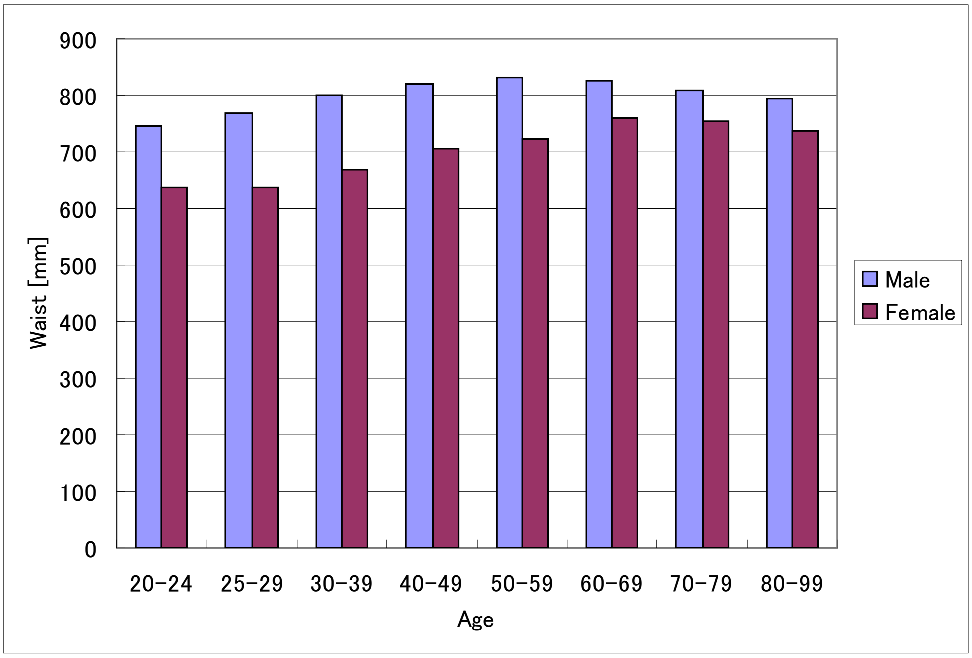
Customized Height, Weight and Waist distributions for our research from the anthropometric database



A-3.1Customized Height distributions of the database for different age layer



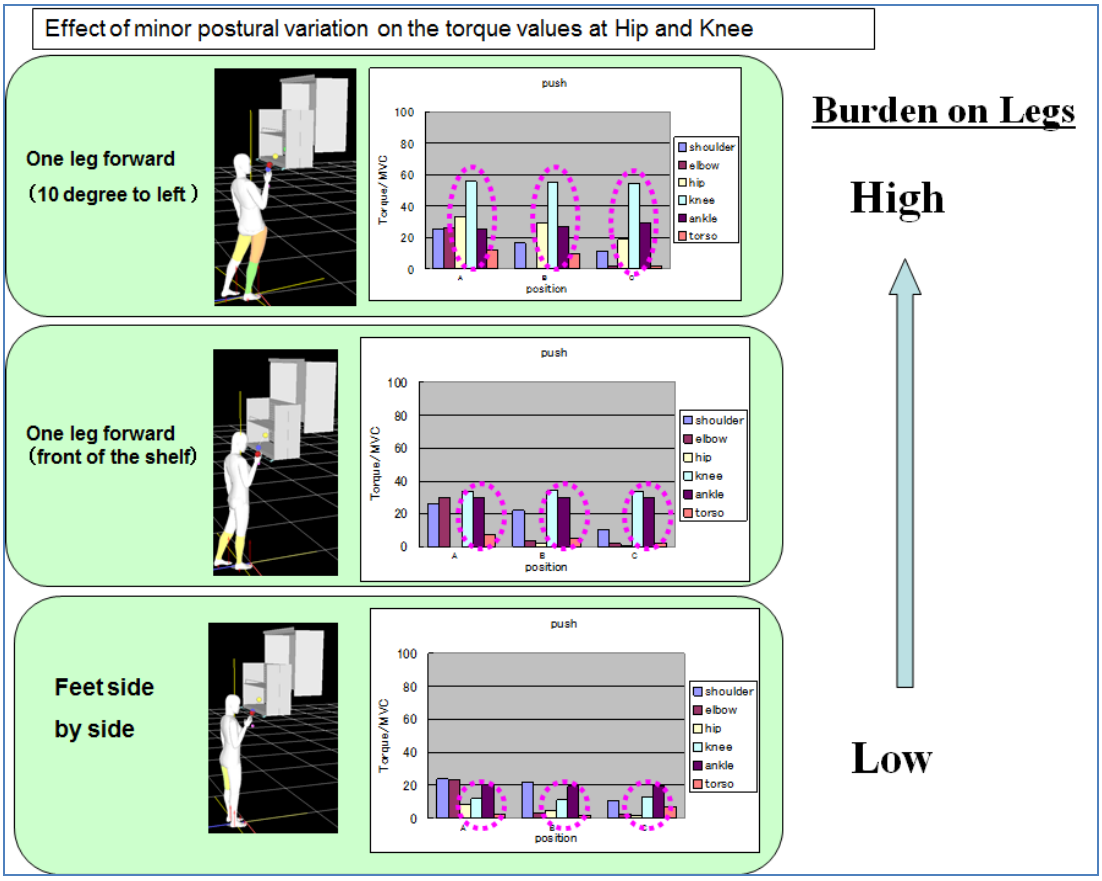
A-3.2 Customized Weight distribution of the database for different age layer



A-3.3Customized Waist distribution of the database for different age layers

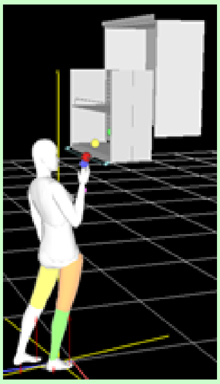
Appendix B

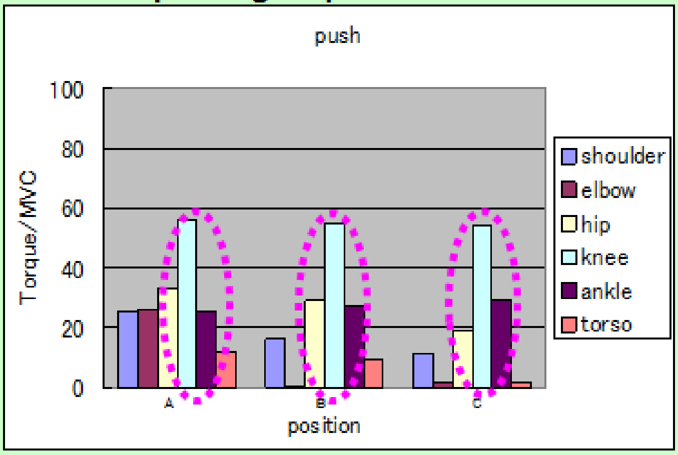
Effect on exerted torque values due to minor changes in Postural variation



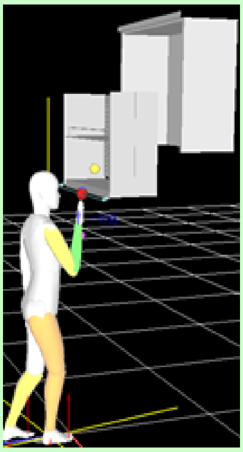
Same Foot Position and adjustment of the posture based on the posture of the real-human subjects

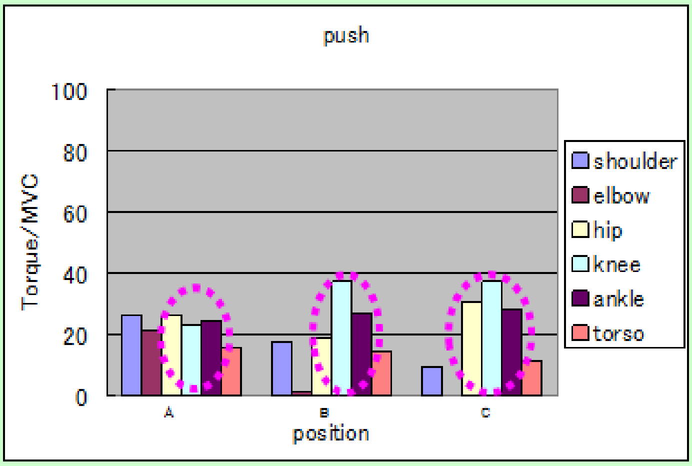
Digital human posture setup by comparing with that of monitor posture – Snapshot and corresponding torques





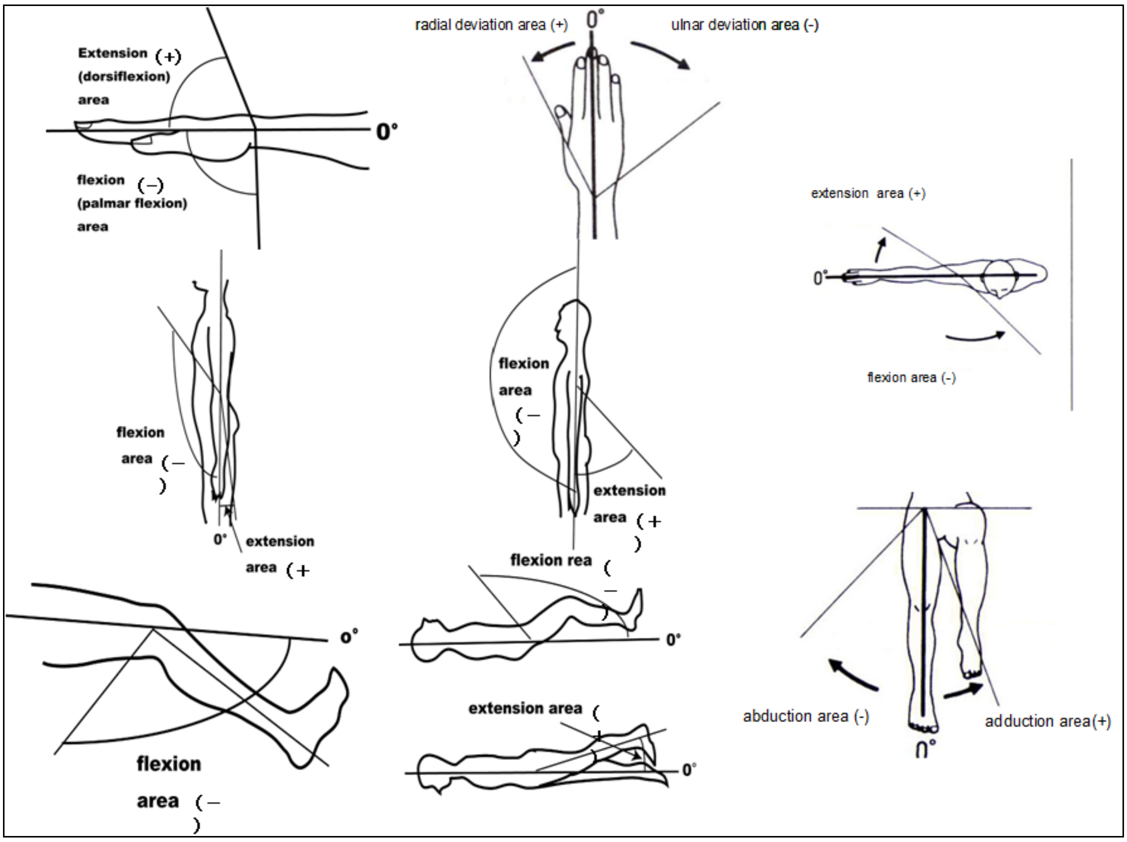
Final approximate set up of the posture with that of monitor and the corresponding torques





Appendix C
Physical Characteristic Database

Appendix C-1
Angle convention in the Physical characteristic database



Appendix C-2
Interpolated MVC values and estimated equations for Hip and Knee Joints

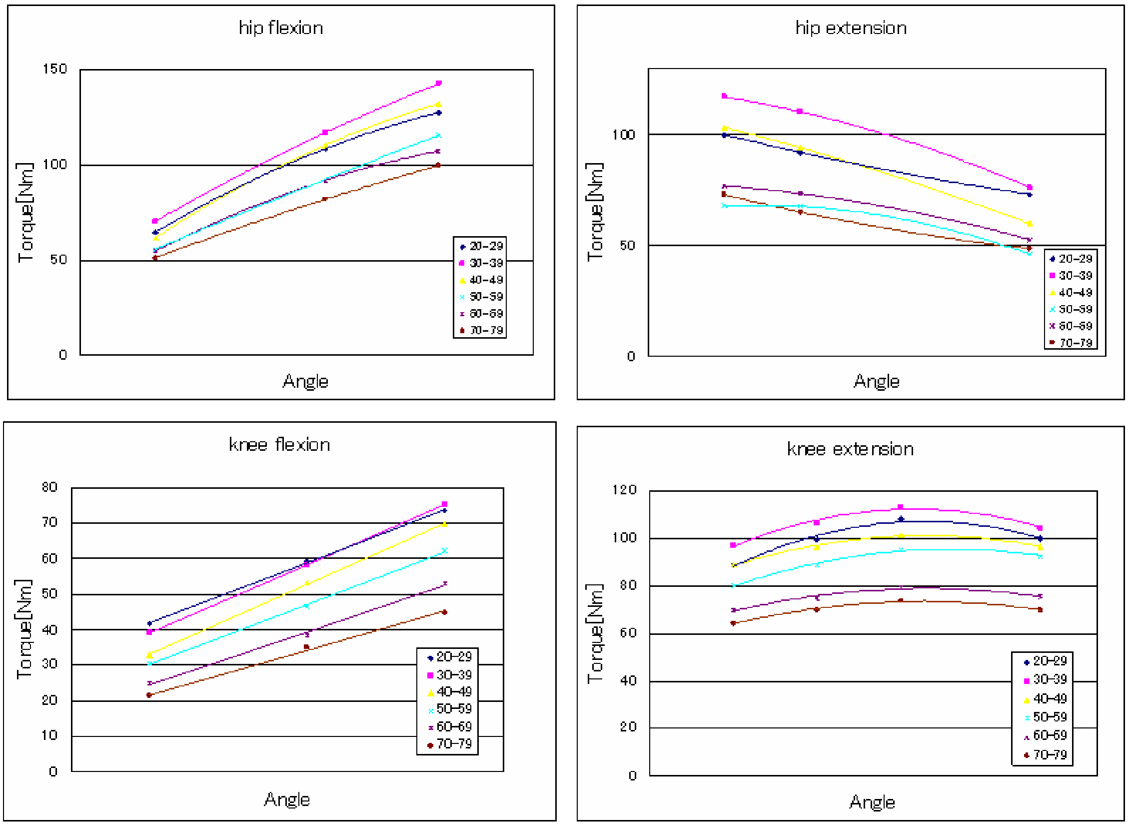


Figure C.1 Interpolated MVC values for Hip and Knee for different age groups

Figure C.1 shows the interpolated values for extreme joint torque at different angles and the lines with different colors are plotted in the same graph for each age group for hip and knee joints. Predicted mean-strength equations for each age layer for hip and knee are shown in Table C.1

Age	Strength (Knee)	Predicted Mean Strength (Nm)
20 ~ 29	flexion	$S_f = 0.4224\,\alpha_K + 3.9956$
	extension	$S_e = -0.0163\,\alpha_K^2 + 3.5624\,\alpha_K - 87.136$
30 ~ 39	flexion	$S_f = 0.4814\,\alpha_K - 4.24$
	extension	$S_e = -0.0149\,\alpha_K^2 + 3.1952\,\alpha_K - 59.344$
40 ~ 49	flexion	$S_f = 0.4903\,\alpha_K - 10.941$
	extension	$S_e = -0.0106\,\alpha_K^2 + 2.3115\,\alpha_K - 25.303$
50 ~ 59	flexion	$S_f = 0.4226\,\alpha_K - 7.7949$
	extension	$S_e = -0.0103\,\alpha_K^2 + 2.3443\,\alpha_K - 37.941$
60 ~ 69	flexion	$S_f = 0.372\,\alpha_K - 8.8803$
	extension	$S_e = -0.0079\,\alpha_K^2 + 1.7299\,\alpha_K - 15.806$
70 ~ 79	flexion	$S_f = 0.3144\,\alpha_K - 6.5478$
	extension	$S_e = -0.0082\,\alpha_K^2 + 1.7797\,\alpha_K - 23.479$

Age	Strength (Hip)	Predicted Mean Strength (Nm)
20 ~ 29	flexion	$S_f = -0.0046\,\alpha_H^2 + 2.0136\,\alpha_H - 79.27$
	extension	$S_e = 0.0018\,\alpha_H^2 - 0.8176\,\alpha_H + 151.27$
30 ~ 39	flexion	$S_f = -0.0024\,\alpha_H^2 + 1.569\,\alpha_H - 51.662$
	extension	$S_e = -0.0052\,\alpha_H^2 + 0.4057\,\alpha_H + 115.65$
40 ~ 49	flexion	$S_f = -0.0046\,\alpha_H^2 + 2.1247\,\alpha_H - 91.714$
	extension	$S_e = -0.0025\,\alpha_H^2 - 0.2027\,\alpha_H + 132.5$
50 ~ 59	flexion	$S_f = -0.0005\,\alpha_H^2 + 0.933\,\alpha_H - 23.946$
	extension	$S_e = -0.0077\,\alpha_H^2 + 1.25\,\alpha_H + 17.37$
60 ~ 69	flexion	$S_f = -0.0042\,\alpha_H^2 + 1.7727\,\alpha_H - 70.906$
	extension	$S_e = -0.0038\,\alpha_H^2 + 0.3993\,\alpha_H + 68.385$
70 ~ 79	flexion	$S_f = -0.0012\,\alpha_H^2 + 0.9476\,\alpha_H - 24.35$
	extension	$S_e = 0.0025\,\alpha_H^2 - 0.9262\,\alpha_H + 128.42$

Table C1: Estimated Mean-Strength equations for each age layer (for Hip and Knee joints)

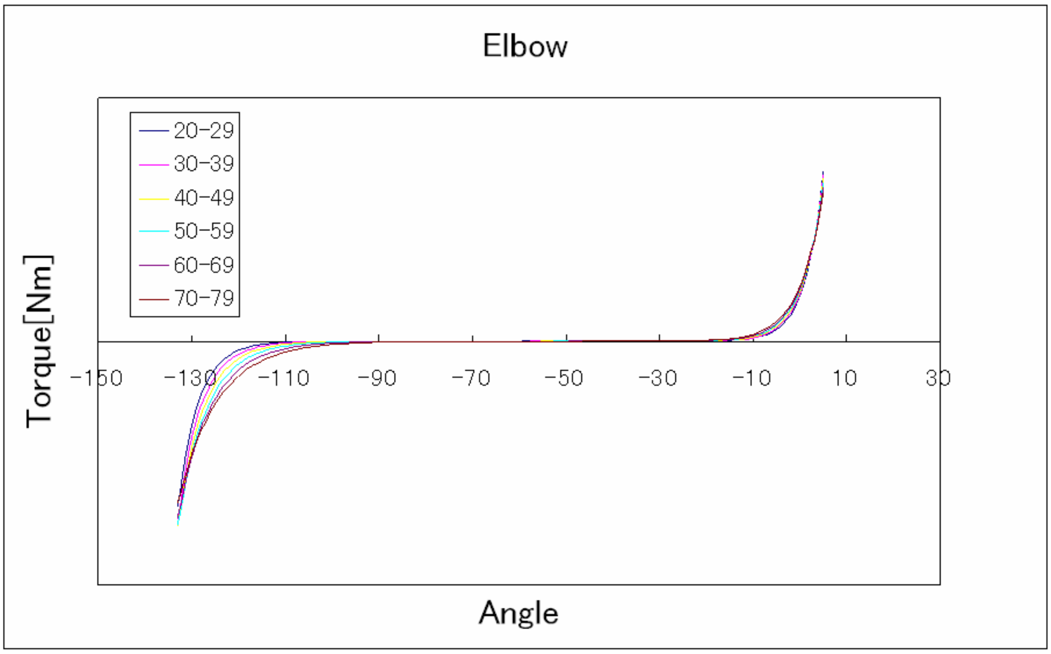
Appendix C-3

Joint Passive Resistance (JPR) for each joint for each age group and the corresponding K values

Elbow

Male	k1	k2	k3	k4	k5	k6
20-29	1	10.92395	0.013192	1	10.19534	-2.29259
30-39	1	8.33847	0.036827	1	8.030569	-2.22157
40-49	1	9.66411	0.045918	1	8.179548	-2.18004
50-59	1	9.396328	0.045635	1	8.986033	-2.30924
60-69	1	10.67285	-0.02551	1	6.819275	-2.19876
70-79	1	10.23044	-0.05475	1	5.200604	-2.18176
80-85	1	12.28147	-0.01106	1	7.185201	-2.26672

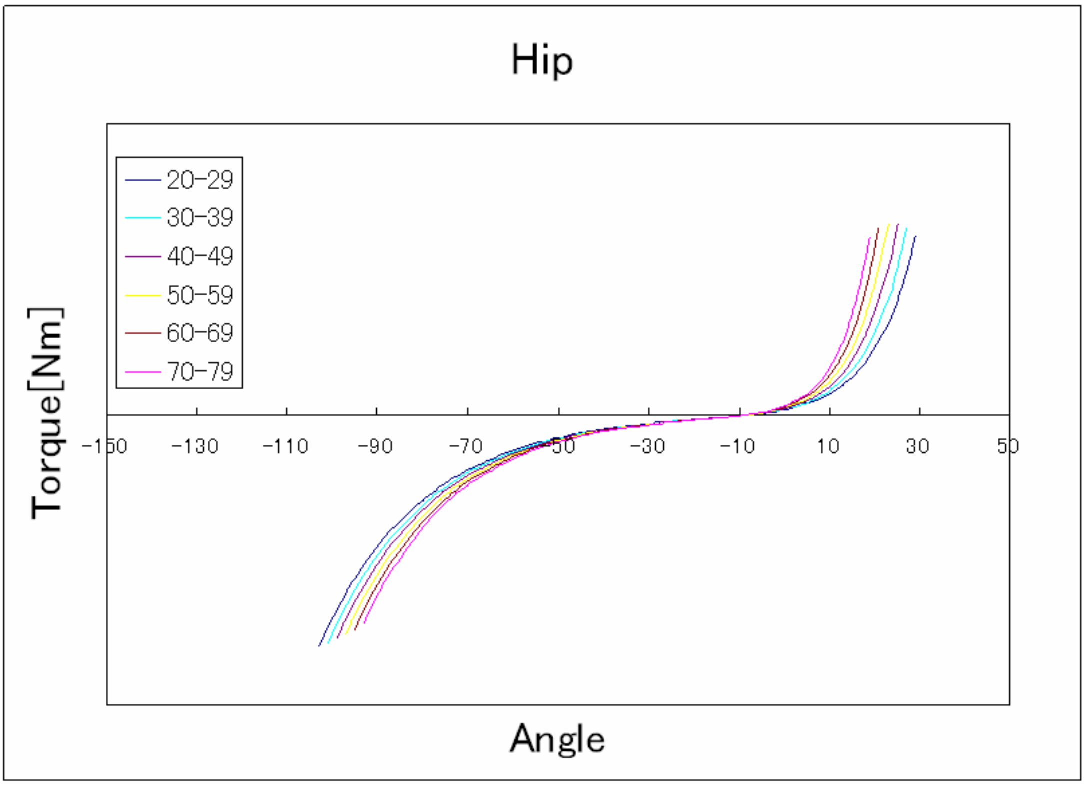
Female	k1	k2	k3	k4	k5	k6
20-29	1	9.823328	0.144261	1	9.667194	-2.37875
30-39	1	8.938331	0.090995	1	8.208102	-2.40164
40-49	1	7.513653	-0.00548	1	8.849647	-2.39979
50-59	1	10.39622	0.101801	1	9.71578	-2.36106
60-69	1	9.969815	0.013932	1	6.621158	-2.28132
70-79	1	9.544006	-0.01626	1	6.945736	-2.30997
80-85	1	16.45694	0.165052	1	11.58653	-2.27071



Hip

Male	k1	k2	k3	k4	k5	k6
20-29	1	4.003154	-0.14623	1	1.974837	-0.07701
30-39	1	4.629245	-0.12149	1	2.231759	-0.19996
40-49	1	4.878455	-0.14024	1	2.122132	-0.22612
50-59	1	5.556134	-0.09618	1	2.055582	-0.1689
60-69	1	6.717611	-0.04793	1	2.040987	-0.18533
70-79	1	6.653933	-0.07213	1	2.065814	-0.2313
80-85	1	5.23987	-0.10167	1	2.186535	-0.55365

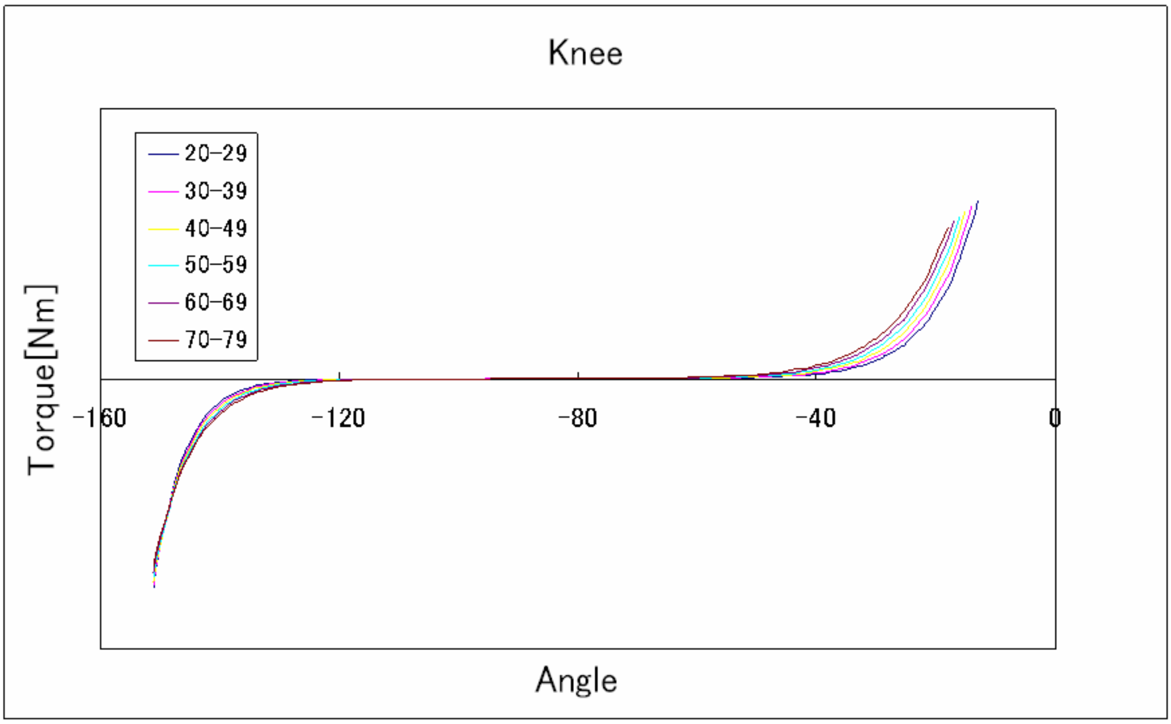
Female	k1	k2	k3	k4	k5	k6
20-29	1	4.080609	-0.14403	1	2.081419	-0.31518
30-39	1	4.229126	-0.0384	1	1.886648	-0.26503
40-49	1	3.80156	-0.09004	1	1.699176	-0.18225
50-59	1	4.106192	-0.08642	1	1.953561	-0.34956
60-69	1	4.873398	-0.05393	1	2.064572	-0.27996
70-79	1	5.822828	-0.02879	1	2.050685	-0.3098
80-85	1	8.530423	-0.03733	1	2.553537	-0.62084



Knee

Male	k1	k2	k3	k4	k5	k6
20-29	1	7.107353	-0.3754	1	11.18996	-2.47892
30-39	1	7.086772	-0.40773	1	10.36122	-2.45521
40-49	1	6.449755	-0.39609	1	10.50661	-2.48481
50-59	1	7.45551	-0.33729	1	8.947203	-2.46719
60-69	1	7.980099	-0.39205	1	9.57386	-2.55746
70-79	1	7.783811	-0.38866	1	9.497883	-2.59058
80-85	1	7.349626	-0.22692	1	9.329901	-2.57484

Female	k1	k2	k3	k4	k5	k6
20-29	1	7.002024	-0.32957	1	10.25801	-2.55871
30-39	1	6.442618	-0.33357	1	11.42709	-2.58172
40-49	1	6.089045	-0.34358	1	9.285432	-2.56274
50-59	1	6.983594	-0.31028	1	10.137	-2.51005
60-69	1	7.149949	-0.39252	1	9.922601	-2.62302
70-79	1	7.952578	-0.38665	1	9.634652	-2.60229
80-85	1	7.357999	-0.42357	1	10.56211	-2.81578



Appendix C-4

The angle, slope and the RMS error at which the exponential growth (of JPR curve) begins for each age group for the different joints

Elbow

Male	Flexion				Extension			
Age	angle	torque	slope	error	angle	torque	slope	error
20-29	-119	-0.110	-1.119	0.182	-13	0.073	0.794	0.167
30-39	-112	-0.116	-0.935	0.122	-16	0.072	0.598	0.094
40-49	-109	-0.102	-0.838	0.111	-13	0.072	0.693	0.127
50-59	-118	-0.105	-0.944	0.137	-13	0.077	0.727	0.129
60-69	-107	-0.104	-0.708	0.079	-16	0.067	0.713	0.146
70-79	-101	-0.113	-0.586	0.051	-18	0.070	0.721	0.141
80-85	-112	-0.106	-0.758	0.089	-13	0.071	0.868	0.207

Female	Flexion				Extension			
Age	angle	torque	slope	error	angle	torque	slope	error
20-29	-124	-0.124	-1.202	0.187	-5	0.103	1.011	0.189
30-39	-123	-0.122	-1.004	0.134	-9	0.109	0.974	0.164
40-49	-124	-0.123	-1.090	0.156	-18	0.098	0.740	0.104
50-59	-123	-0.122	-1.198	0.187	-7	0.098	1.014	0.202
60-69	-113	-0.128	-0.850	0.093	-12	0.108	1.076	0.204
70-79	-115	-0.121	-0.842	0.096	-15	0.096	0.917	0.166
80-85	-120	-0.128	-1.484	0.272	2	0.088	1.450	0.482

Hip

Male	Flexion				Extension			
Age	angle	torque	slope	error	angle	torque	slope	error
20-29	-52	-5.104	-9.983	0.358	7	2.253	10.39	0.893
30-39	-53	-5.014	-11.13	0.439	6	2.342	12.06	1.152
40-49	-57	-5.090	-10.76	0.400	4	2.252	12.46	1.248
50-59	-55	-5.070	-10.39	0.372	5	2.180	14.18	1.609
60-69	-56	-5.029	-10.25	0.361	6	2.234	17.59	2.367
70-79	-58	-5.012	-10.35	0.368	5	2.369	18.14	2.402
80-85	-74	-5.011	-10.95	0.411	4	2.200	12.31	1.253

Female	Flexion				Extension			
Age	angle	torque	slope	error	angle	torque	slope	error
20-29	-62	-4.907	-10.17	0.372	6	2.342	10.39	0.862
30-39	-64	-4.974	-9.360	0.308	12	2.442	11.29	0.948
40-49	-64	-4.871	-8.234	0.248	11	2.391	10.20	0.788
50-59	-67	-4.943	-9.632	0.328	9	2.345	10.43	0.853
60-69	-60	-4.861	-10.01	0.359	9	2.390	12.79	1.238
70-79	-62	-4.866	-9.969	0.352	8	2.267	14.70	1.688
80-85	-71	-4.842	-12.36	0.539	4	2.322	20.83	3.432

Knee

Male	Flexion				Extension			
Age	angle	torque	slope	error	Angle	torque	slope	Error
20-29	-130	-0.094	-1.054	0.187	-35	0.188	1.336	0.176
30-39	-128	-0.100	-1.035	0.171	-37	0.186	1.315	0.173
40-49	-130	-0.102	-1.074	0.180	-38	0.179	1.154	0.137
50-59	-126	-0.090	-0.805	0.116	-32	0.193	1.436	0.199
60-69	-132	-0.087	-0.835	0.128	-35	0.175	1.396	0.208
70-79	-134	-0.090	-0.859	0.131	-35	0.178	1.384	0.201
80-85	-133	-0.093	-0.866	0.130	-26	0.189	1.389	0.190

Female	Flexion				Extension			
Age	angle	torque	slope	error	angle	torque	slope	error
20-29	-134	-0.103	-1.061	0.174	-32	0.202	1.412	0.183
30-39	-137	-0.112	-1.276	0.231	-33	0.210	1.354	0.161
40-49	-133	-0.105	-0.976	0.146	-35	0.197	1.198	0.134
50-59	-131	-0.102	-1.038	0.168	-31	0.200	1.396	0.181
60-69	-137	-0.099	-0.982	0.156	-35	0.210	1.504	0.200
70-79	-136	-0.109	-1.052	0.163	-34	0.194	1.540	0.230
80-85	-149	-0.102	-1.072	0.180	-37	0.195	1.438	0.197

Appendix D: Maximum Compressive force and the corresponding Torso Torque (Using Jager & Genaidy Judgement)

Jager Judgement manikin : female 160cm 60kg		
age	Fc Max(KN)	L5/S1(Torso) Torque(Nm)
20	4.44	218
21	4.375	215
22	4.31	212
23	4.245	208
24	4.18	205
25	4.115	202
26	4.05	197
27	3.985	194
28	3.92	192
29	3.855	187
30	3.79	184
31	3.725	181
32	3.66	177
33	3.595	174
34	3.53	171
35	3.465	167
36	3.4	164
37	3.335	161
38	3.27	156
39	3.205	153
40	3.14	150
41	3.075	146
42	3.01	143
43	2.945	140
44	2.88	136
45	2.815	133
46	2.75	130
47	2.685	126
48	2.62	123
49	2.555	120
50	2.49	115
51	2.425	113
52	2.36	110
53	2.295	105
54	2.23	102
55	2.165	99
56	2.1	95
57	2.035	92
58	1.97	88
59	1.905	85
60	1.84	82
61	1.775	78
62	1.71	75
63	1.645	72
64	1.58	68
65	1.515	65
66	1.45	62
67	1.385	57
68	1.32	54
69	1.255	51
70	1.19	47
71	1.125	44
72	1.06	40
73	0.995	37
74	0.93	34
75	0.865	30
76	0.8	27
77	0.735	24
78	0.67	20
79	0.605	17
80	0.54	14
81	0.475	9
82	0.41	7
83	0.345	2
84	0.28	2
85	0.215	1

Genaidy Judgement manikin : female 160cm Weight is variable					
age	Fc Max(KN)				
	40kg	50kg	60kg	70kg	80kg
20	3.523	4.118	4.713	5.308	5.903
21	3.468	4.063	4.658	5.253	5.848
22	3.413	4.008	4.603	5.198	5.793
23	3.358	3.953	4.548	5.143	5.738
24	3.303	3.898	4.493	5.088	5.683
25	3.248	3.843	4.438	5.033	5.628
26	3.193	3.788	4.383	4.978	5.573
27	3.139	3.733	4.328	4.923	5.518
28	3.084	3.678	4.273	4.868	5.463
29	3.029	3.624	4.218	4.813	5.408
30	2.974	3.569	4.164	4.758	5.353
31	2.919	3.514	4.109	4.704	5.298
32	2.864	3.459	4.054	4.649	5.244
33	2.809	3.404	3.999	4.594	5.189
34	2.754	3.349	3.944	4.539	5.134
35	2.699	3.294	3.889	4.484	5.079
36	2.644	3.239	3.834	4.429	5.024
37	2.589	3.184	3.779	4.374	4.969
38	2.534	3.129	3.724	4.319	4.914
39	2.479	3.074	3.669	4.264	4.859
40	2.424	3.019	3.614	4.209	4.804
41	2.369	2.964	3.559	4.154	4.749
42	2.314	2.909	3.504	4.099	4.694
43	2.259	2.854	3.449	4.044	4.639
44	2.204	2.799	3.394	3.989	4.584
45	2.149	2.744	3.339	3.934	4.529
46	2.095	2.689	3.284	3.879	4.474
47	2.04	2.635	3.229	3.824	4.419
48	1.985	2.58	3.175	3.769	4.364
49	1.93	2.525	3.12	3.715	4.309
50	1.875	2.47	3.065	3.66	4.255
51	1.82	2.415	3.01	3.605	4.2
52	1.765	2.36	2.955	3.55	4.145
53	1.71	2.305	2.9	3.495	4.09
54	1.655	2.25	2.845	3.44	4.035
55	1.6	2.195	2.79	3.385	3.98
56	1.545	2.14	2.735	3.33	3.925
57	1.49	2.085	2.68	3.275	3.87
58	1.435	2.03	2.625	3.22	3.815
59	1.38	1.975	2.57	3.165	3.76
60	1.325	1.92	2.515	3.11	3.705
61	1.27	1.865	2.46	3.055	3.65
62	1.215	1.81	2.405	3	3.595
63	1.16	1.755	2.35	2.945	3.54
64	1.105	1.7	2.295	2.89	3.485
65	1.051	1.645	2.24	2.835	3.43
66	0.996	1.591	2.185	2.78	3.375
67	0.941	1.536	2.131	2.725	3.32
68	0.886	1.481	2.076	2.671	3.265
69	0.831	1.426	2.021	2.616	3.211
70	0.776	1.371	1.966	2.561	3.156
71	0.721	1.316	1.911	2.506	3.101
72	0.666	1.261	1.856	2.451	3.046
73	0.611	1.206	1.801	2.396	2.991
74	0.556	1.151	1.746	2.341	2.936
75	0.501	1.096	1.691	2.286	2.881
76	0.446	1.041	1.636	2.231	2.826
77	0.391	0.986	1.581	2.176	2.771
78	0.336	0.931	1.526	2.121	2.716
79	0.281	0.876	1.471	2.066	2.661
80	0.226	0.821	1.416	2.011	2.606
81	0.171	0.766	1.361	1.956	2.551
82	0.116	0.711	1.306	1.901	2.496
83	0.062	0.656	1.251	1.846	2.441
84	0.007	0.602	1.196	1.791	2.386
85	−0.048	0.547	1.141	1.736	2.331

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  - **CyberDome – Best Industrial Design and Simulation**
- **Excellent Paper Award** IAUD 2010, October

Patents:

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  ApplicationNo.WO2010 72226
  ApplicationNo.WO2009 062519

- **Japanese Patent Pending**

  ApplicationNo.JP2010-052121
  ApplicationNo.JP2009-219206

ApplicationNo.JP2008-324563
ApplicationNo.JP2006-162710
ApplicationNo.JP2006-152502
ApplicationNo.JP2005-261216

- **Japanese Patents Received**

Patent No JP4692175
Patent No JP4622570
Patent No JP4270088
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Publications:

1. "An Ergonomic Simulator as a Universal Design Tool using Digital Human Ageing Simulation", Hareesh, Terashima, Someya, Sawada, D. Thalmann, International Conference on Universal Design (IAUD 2010), October, Japan (***Excellent Paper Award***)
2. "An Ergonomic Evaluation Engine for Conceptual Design Stage Using Anthropometric Digital Human Models" Hareesh, Kimura, Adachi, D. Thalmann. 11th International Design Conference, Croatia, May 2010
3. "Ageing Algorithm for Anthropometric DigitalHumans: Quantitative Estimation for Ergonomic Applications" Hareesh, Kimura, Sawada, D. Thalmann, IAENG International Conference on Industrial Engineering (ICINDE'10), Honkong , March 2010
4. "Anthropometric Digital Human Models in Universal Design: Demonstration with a few Applications", Hareesh P V, Sawada K, Thalmann D : 10th Annual Conference VRSJ 2005, Japan
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