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Aging Algorithm for Anthropometric Digital Humans: Quantitative Estimation for Ergonomic Applications

P V Hareesh, T.Kimura, K Sawada and D. Thalmann.

Abstract— **This paper introduces an approach to estimate the effect of aging on surface anthropometry, articulation limits and physical strength for digital humans at joint level. By making use of an anthropometric database, physical characteristic database and prioritized Inverse Kinematics architecture, the developed simulation system could be a core engine for ergonomic analysis at the conceptual design stage of a product development cycle. The proposed system could be an efficient tool for helping designers more quickly and easily identify ergonomic flaws. The results have been validated with real human subjects indicating the practical implication of the total system as an ergonomic design tool.**

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***Index Terms*—digital humans, anthropometry, aging algorithm, conceptual design**

I. Introduction

"Fitting the Human to the System -> Fitting the System to the Human". Engineering design is in the midst of this paradigm shift and human centered product design has become increasingly important to the survival in the global market. "To make your home the home of future - a home that is safer and more comfortable at all ages" is one of the statements underlying the concept of "universal design," a concept that is becoming more and more important as the aging population is increasing.

The traditional way to realize and identify an ergonomic problem is to visualize it through the evaluation of physical product mock-ups by 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 [Fig 1].

Both the shrinking time frames for product design and, manufacture, and consumer demands for more convenience comfort, and safety, point to the need for a digital human interface and design tools with specific population attributes

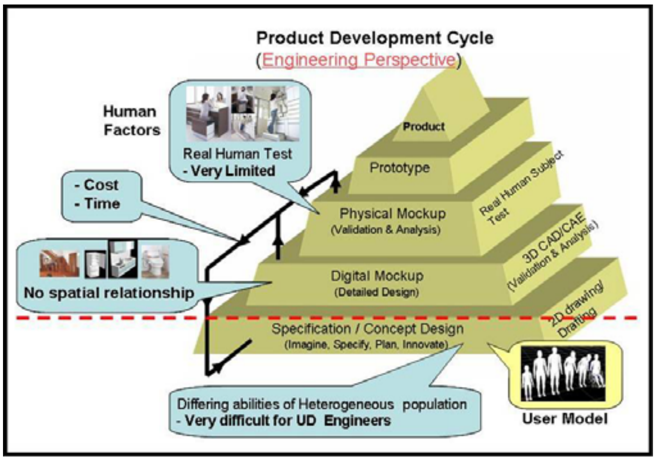

Fig 1 Necessity of User-model of heterogeneous population at the conceptual design stage in a product development cycle

that can be merged with 3D graphics renderings of proposed work environments.

The Digital Human Modeling (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. Today, the most widely used commercial DHM packages include Jack, Ramsis, Safework, Man3D, AnyBody . However, these packages and most conventional DHM techniques have not yet addressed the needs of the growing aging population in many societies across the globe. This paper aims at introducing an approach to estimate the effects of aging on articular limits, strengths and surface anthropometry that are sufficient to analyze the ergonomic aspect of a product at its very conceptual design stage. The paper is organized as follows. Section 2 defines the scope of this work. The proposed system and methods are described in section 3. Validation of the results and the practical usage of the system are described in Section 4 and the paper concludes in Section 5.

II. Digital Human Technology and the Scope of the Research

The Digital Human creation of varying level of detail using computer graphics is a well-documented topic [1]-[4]. An overview of the current developments in digital human modeling can be found in [5], 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

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Anybody modeling system [6]. 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 are JACK and RAMSIS and they have been mostly applied in automobile industry.

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. The focus of our research is to incorporate human factors at the conceptual design stage by replacing 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. Accordingly our digital human models have been limited to biomechanical models consisting of a hierarchy of rigid segments connected by joints at the most basic level. The scope of the aging algorithm proposed in this paper should be viewed in that context. With the knowledge of internal joint torques it is possible to simulate external forces, postures and motions without having a detailed understanding of the underlying muscle activities [7]. Articulated biomechanical models have been reported by many researchers for ergonomic applications. Chaffin gives comprehensive analysis techniques in his book [8] and Ayoub et al shows mathematical approach in their book [9]. Our research will be complementary to those prior investigations by adding aging module as the key factor. Our strategy can be distinguished from others because of following characteristics. Our approach is empirical and our models derive directly from data.

III. Total System Architecture

The total simulation can be described by dividing the whole system into three steps depending on the body, its strength and its motion for digital humans. ***Step 1*** deals with the method of generating surface anthropometry based on age. Physical strength estimation will be described in ***Step 2*** and ***Step 3*** describes briefly the motion techniques for real time action generation.

A. Step 1 : Surface Anthropometry Estimation Based on Age

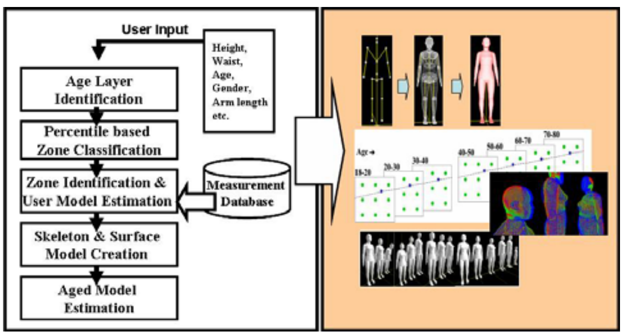

Fig 2 Overview of Step 1 - Surface Anthropometry Estimation

To create surface anthropometry we make use of an anthropometric database of 34,000 people in Japan (HQL). (http://riodb.ibase.aist.go.jp/dhbodydb/) and Fig 2 shows the overview of the ***Step 1*** strategy.

First of all, the database has been customized in to "age layers" with age groups of 10 years, providing us with the age groups of 20-29, 30-39,40-49,50-59,60-69,70-79. Each layer is then further divided into 9 patterns on a percentile basis, so that all the measurements are distributed in nine groups of percentiles ((5,5),(5,50),(5,95), (50,5),(50,50), (50,95), (95,5), (95,50), (95,95)) in that particular layer. Each layer is 3-dimensional marked with axes for height, waist and weight parameters and it is classified into 8 zones [Fig 4]. To extract the surface anthropometry of the user, after determining the age layer, a 2-dimensional layer for the given weight is selected and the appropriate zone is estimated on the height and waist of the user. All anthropometric measures [Fig 3] of the user are then computed as a vector sum values of the available data in the selected zone of the database. Using this customized database, our system can create empirically validated digital humans of any size, height, age, waist, and weight and arm lengths [Fig 4].

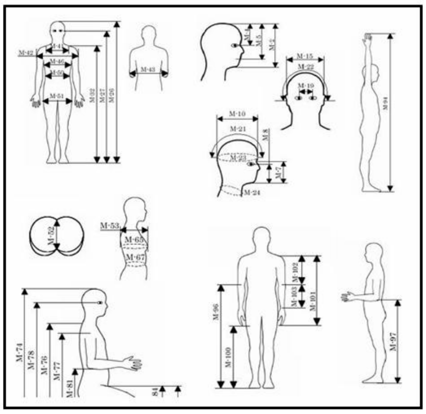

Fig 3 Measurement examples in the Database

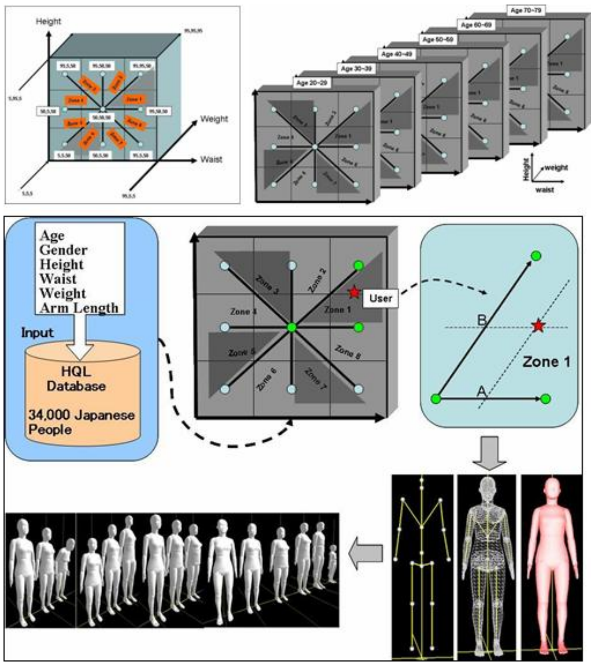

Fig 4 method of creating the User-model from the database, with an example of user value placed at Zone 1

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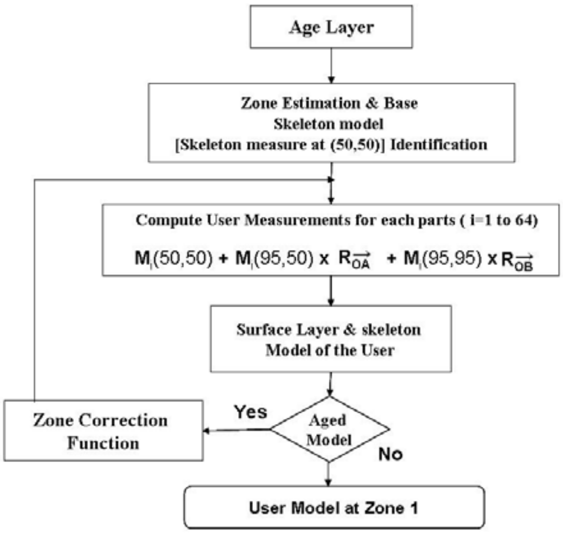

Fig 5 Overview of the data-flow to generate a user-model that is placed in Zone 1

The data flow and the step by step approach of estimating the user model are shown in Fig 4 and 5, by considering the position of the user model in zone 1, as an example.

Based on the height and waist of the user, a zone is identified as Zone 1 [Fig 4] and his/her measurements are extrapolated using the measures at 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.

B. Step 2 : Physical Strength Estimation Based on Age

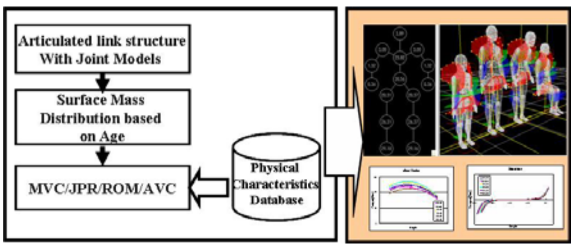

Fig 6 Overview of Step 2 – Strength Estimation

Towards the physical strength estimation, the whole body model is upgraded to the biomechanical model that has articulated link structure with joint models. Joints are classified according to the type of motion they allow. The body balance is obtained by controlling the position of the centre of mass with a technique called inverse kinetics, which integrates the body mass distribution information for single or multiple supports. 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 [10][11] 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 fig 7

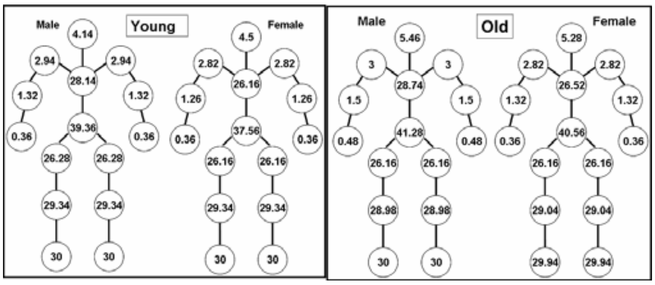

Fig 7 Body mass distribution using augmented body concept for both young and old , with an example weight of 60 kg

For ergonomic applications, the developed articulated biomechanical digital human simulation will not be sufficient to analyze the human factors if we do not have a method by which designers can validate whether the joint torques generated by digital human for a particular posture is permissible or within the affordable limits. These methods should include the validation techniques for a single digital human as well as for the aging population. Chaffin [13] 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 by making use of a physical characteristic database of actual human subjects.

The strength is being estimated by using a database developed by National Institute of Technology and Evaluation and is publicly available since 2002 [14] [15]. Towards the strength estimation for digital humans, the database has been customized based on different age groups (20-29, 30-39, 40-49, 50-59, 60-69, 70-79) and the diagram 8 shows the variation of maximum strength of the subjects in the customized database for the elbow joint. Readers are requested to refer the appendix A for the remaining joints.

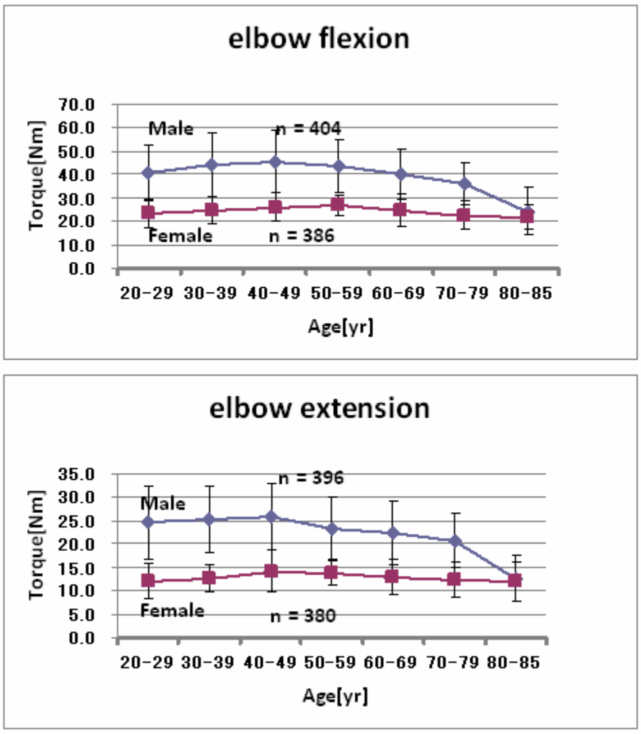

Fig 8 Variation of Maximum Strength of the subjects and Standard Deviation (SD) for each age layer for Elbow Joints (Red line – Female, blue line – male)

Total number of subjects available in each age group is shown in Fig 9

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age	male	female	total
20-29	39	36	75
30-39	54	37	91
40-49	49	34	83
50-59	46	46	92
60-69	208	202	410
70-79	142	116	258
80-89	12	7	19
Total	550	478	1028

Fig 9 Number of subjects available in each age layer

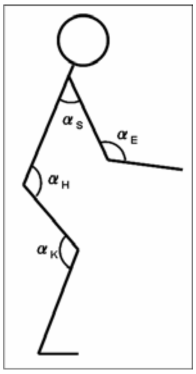

Fig 10 (A) Joint angles used in equations in Fig 10 (B)

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	$-S = (342.8[AF] - 0.0996\,\alpha_K + 0.17308\,\alpha_K^2 - 0.00097\,\alpha_K^3)*0.0603$

Fig 10 (B) Aging equations for mean strength for male and female

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

Fig 11 Age correction coefficients (AF) for both genders

The derived coefficients for predicted mean strength for different ages are then merged with Chaffin equations as age correction coefficients. Fig 10 shows the modified Mean strength equations corrected for different age groups and age factor coefficients (AF) for both male and female and for each joints are listed in Fig 11

To estimate affordable strength (AVC) of an individual at a particular age range, the available database was not sufficient and we had to do further experiments with hundreds of different subjects using Biodex System [Fig 12 (B)].

The AVC strategy for a digital human in the case of shoulder flexion/extension is shown in Fig 12(A). Joint angle being on the x-axis and Torque on y-axis, the colored portions show the predicted easy (green), difficult (yellow) and very difficult (red) zones for the shoulder movements. In the Y-axis, when the load increases at a particular joint angle, the digital human is said to be moving from easy zone to difficult zones. Percentage values of Mean strength (We use this term as AVC, meaning affordable voluntary contraction) that are affordable for daily activities (for each joint) are estimated

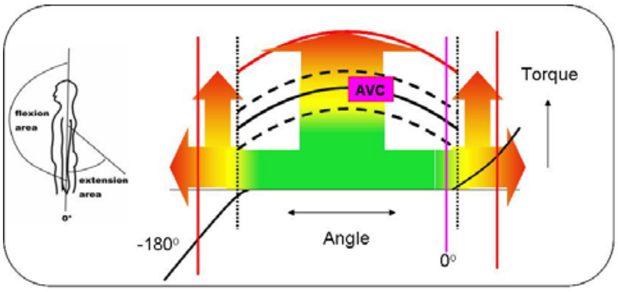

Fig 12 (A) Strategy to estimate AVC

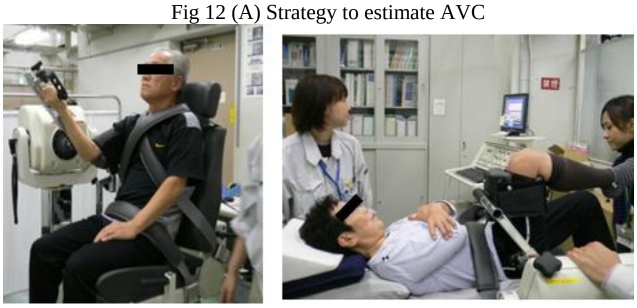

Fig 12 (B) Snapshots of the method of estimating AVC

and incorporated into the total simulation system. The results are listed in Fig 13

JOINT	%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%

Fig 13 Affordable Voluntary Contraction (AVC)

For passive resistance (JPR), the data has been analyzed near the joint extremes and age related parameters 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 Fig 14. An exponential function for Joint moment to angle can be expressed as the following

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

The curves of exponential growth are determined by K3 and K6. It is found that K6 increases and K3 decreases when age increases.

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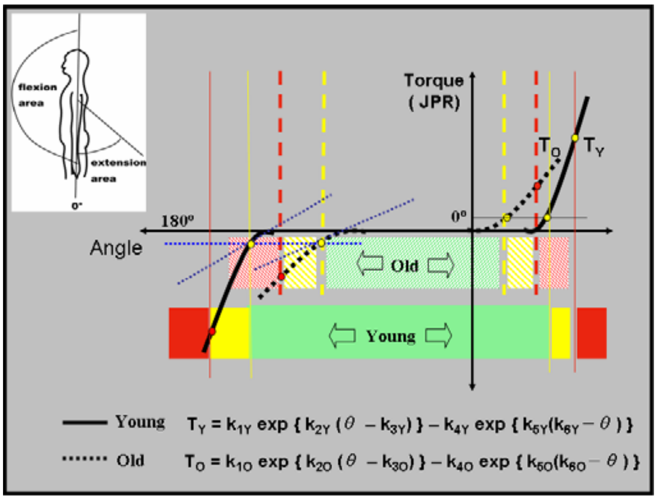

Fig 14 Strategy for determining easy, difficult and very difficult zones near the joint limits (Using Joint Passive Resistance, JPR)

Joint moment equations for each age layer are determined and the graph for the shoulder joint is shown in Fig 15. 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

$$\sum \left|T(\theta_i)\text{-}Ti(\theta_i)\right|^2$$

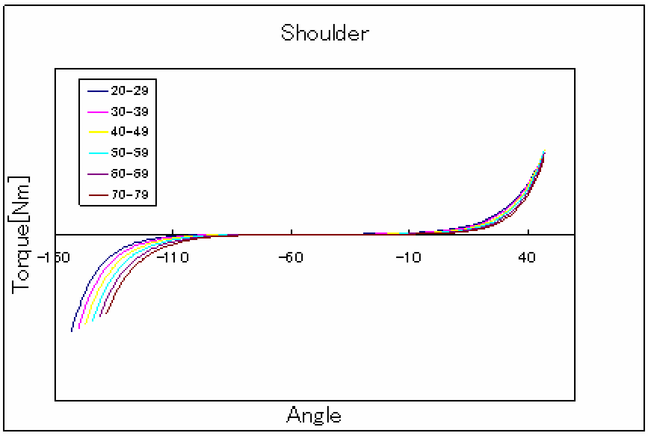

Fig 15 Joint Passive Resistance (JPR) for Shoulder Joint based on age

Readers are requested to refer the appendix B for other joints.

C. Step 3: Real-Time Posture & Motion Generation

The motion of digital human is entirely controlled by a hierarchically articulated structure. We use H-Anim standard [16] as the basis of the articulated structure. By defining a few high level handles, the posture of a digital human can be driven synergistically for a task by making use of prioritized Inverse Kinematics Architecture [17][18].

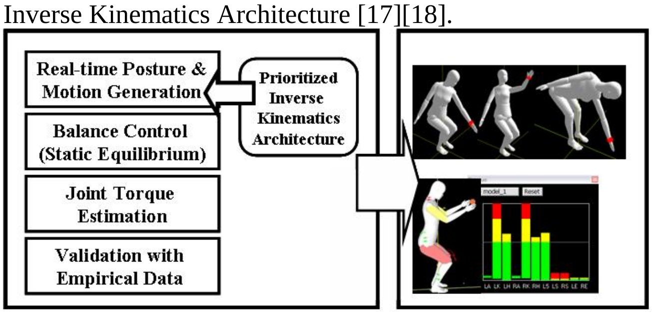

Fig 16 Overview of Step 3 – Real-Time motion control

Using the developed system, even a non-specialist user can control anthropometric digital human postures intuitively in real time [Fig 17]

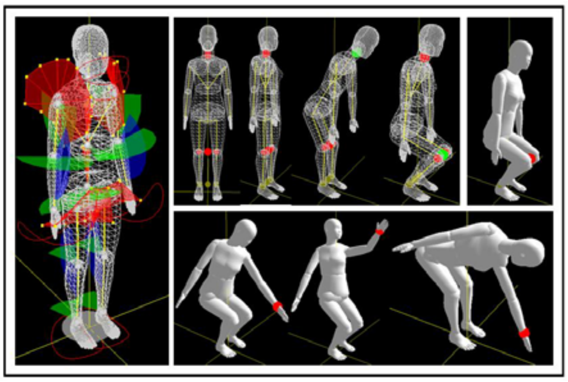

Fig 17 Intuitive Motion and posture control of digital humans using prioritized Inverse Kinematics

The mechanism used for the posture evaluation is based on a musculoskeletal load assessment method proposed by Chaffin and Baker [12]. External forces acting on a body segment under gravity produce load moments at body joints. These load moments can be compared to muscle strength moments and thus provide a means to evaluate the stress-level of particular joints.

IV. Discussion

A. Functional Assessment of the Simulation

Towards the functional assessment of the digital human simulation, experiments have been conducted. A few validation methods that we used are as follows

1) 1. Validation, based on the feed back from actual human subjects

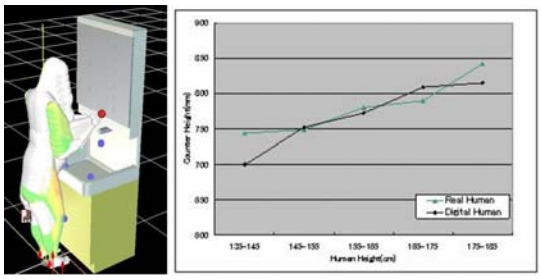

Fig 18 Comparison of the digital human results with that of actual human subjects

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 [Fig 18] shows the decision made by the digital humans and the green line shows the one made by real subjects.

2) Validation by analyzing the trajectory of a pull-down shelf (And comparing the EMG values of monitor and shoulder torque of digital humans)

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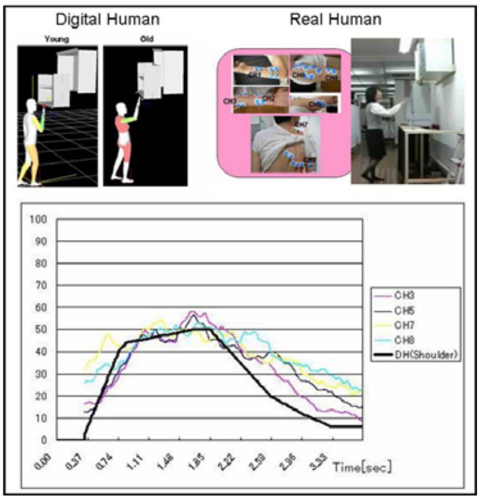

Fig 19 Comparison of the digital human results with that of EMG values of real human subjects

The focused application is a pull-down shelf of a kitchen. In the context of designing a Universal design kitchen shelf, 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. It is found that the diagonal trajectory is the optimal solution for a wide range of population.

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[Fig 19] 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.

B. Practical Usage of the Simulation as a Design Tool

Towards the practical application, an ergonomic evaluation engine has been developed. Using an intuitive control facility, the design engineers can input a simple CAD model, design variables and human factors into the system. The evaluation engine generates the required simulation in real time. Some design variables and simulation examples are shown in Fig 20.

V. Conclusion

This paper introduced an approach to estimate the effect of aging on surface anthropometry, articulation limits and physical strength at joint level. The potential use of these results in anthropometric digital human models has been discussed. By making use of an anthropometric database, the physical characteristic database and prioritized Inverse Kinematics architecture, the developed simulation system could be a core engine for the ergonomic analysis at the very conceptual design stage of product development cycle. 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 there by indicating the practical implication of the total system as an ergonomic design tool.

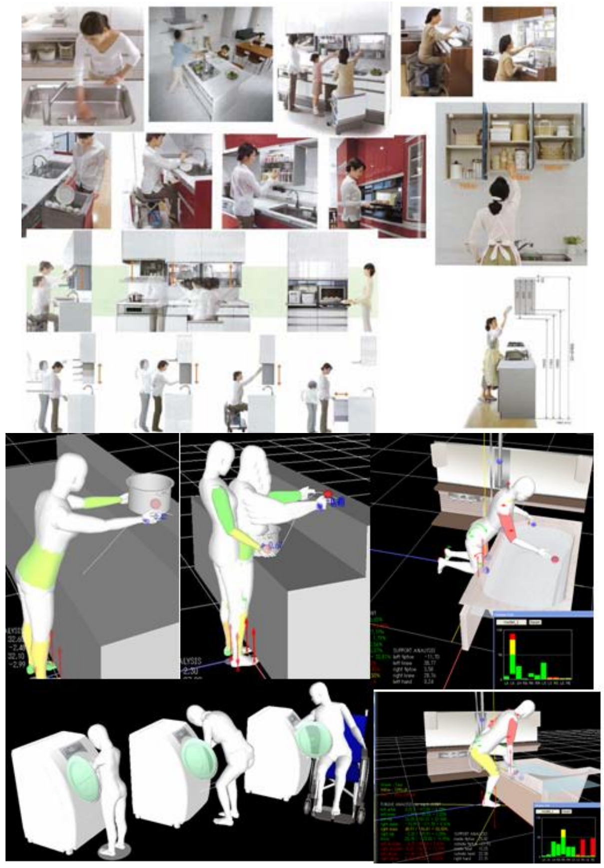

Fig 20 Design variables (top) and Snapshots of the simulation

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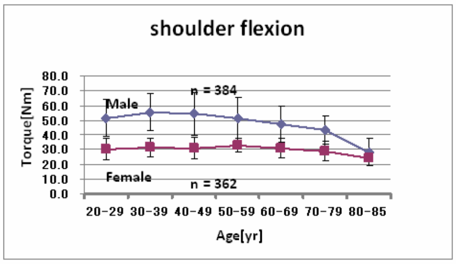
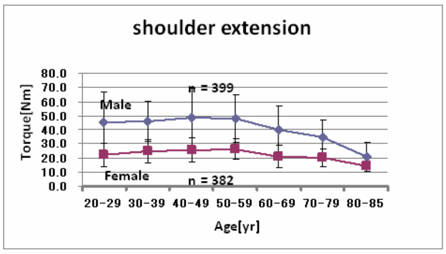
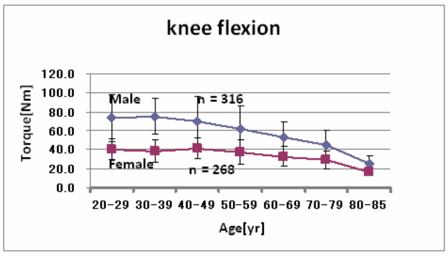
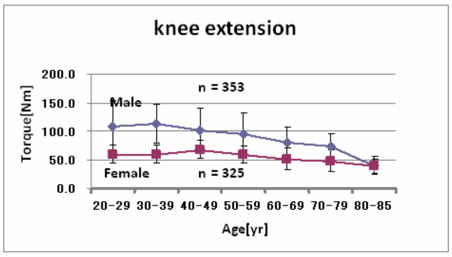
APPENDIX A

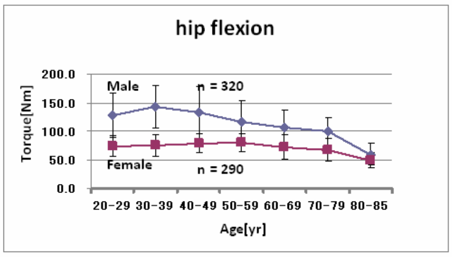
Variation of Maximum Strength of the subjects and Standard Deviation (SD) for each age layer for Shoulder, Knee and Hip Joints (Red line – Female, blue line – male)

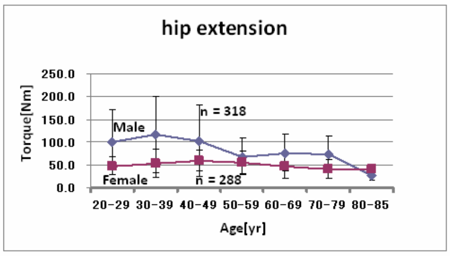






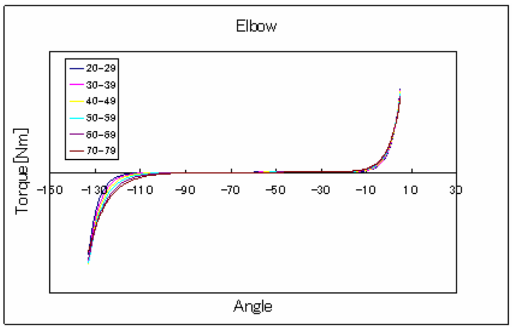


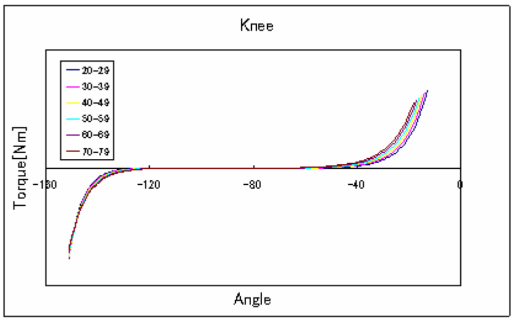


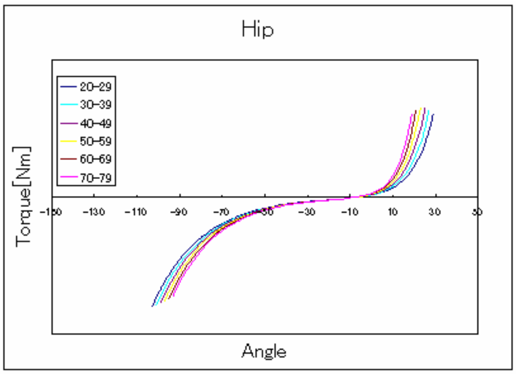


APPENDIX B

Joint Passive Resistance (JPR) for Elbow, Knee and Hip joints based on age。







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