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AN ERGONOMIC EVALUATION ENGINE FOR CONCEPTUAL DESIGN STAGE USING ANTHROPOMETRIC DIGITAL HUMAN MODELS

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1. Introduction

Human-centered product design has become ever more important in order to survive in the global market. Rapid growth in aging population and the stagnant home appliance market are prompting designers to pay much more attention to barrier-free and Universal designs (UD)
Designing a product that could "be used more easily by more people" is not a trivial task. It is very difficult to evaluate a design from many people's view points. UD engineers have to infer the differing abilities of a heterogeneous population. 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. For easier and earlier identification of ergonomic design flaws, imagine if we could have user model readily available at the conceptual design stage of product development cycle. Focus of this paper is to introduce such a system which incorporates Conceptual design, design variables and digital human models [see Figure 1]

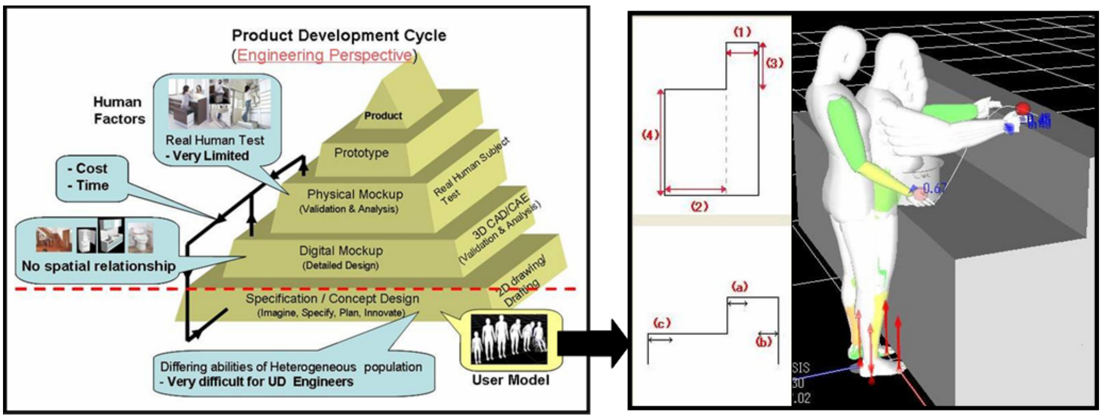


Figure 1. Earlier identification of Human Factors by introducing User Model at the Conceptual Design Stage

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 modelling can be found in [Duffy, 2009], 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 modelling system [Rasmussen, 2004]. 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, all contributing to slow production pipelines. They have also not addressed the needs of the growing aging population in many societies across the globe. These expensive packages also have a very poor CAD system and User Interfaces.

We aim at incorporating 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. 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 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. 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.

The paper is organized as follows. Section 2 describes the key component of our total system. Strategy for the usage of this system as an Ergonomic Evaluation Engine and results with practical application examples and advantages of the system are explained in Section 3 and the paper concludes in Section 4.

2. Key components of our developed System

The basic building blocks to set up an ergonomic evaluation engine at the conceptual design stage can be listed as the following

1. Functions and methods to create user model of hetrogenous population
2. Functions to create 3D product model (using primitive geometries) from 2d images/drawing
3. Interface functions between user model and product model
4. Assessment functions for ergonomic evaluation
5. Viewer and interface functions

The key components of the developed system are described in detail below.

2.1 Functions and methods to create user model using digital human technology

Digital Human creation of varying level of detail using computer graphics is a well-documented topic [Duffy, 2009]-[Badler, 2002]. A digital human model can be broadly classified into physical, physiological and psychological models. Our research focus at the moment is limited to Physical model that consists of a hierarchy of rigid segments connected by joints at the most basic level. With the knowledge of internal joint torques it is possible to simulate external forces, postures and motions without the need of having a detailed understanding of the underlying muscle activities [Badler, 2002]. An abstract overview of our developed digital human system is shown in Figure 2. The whole system is divided in to three steps depending on the body, its motion and its strength.

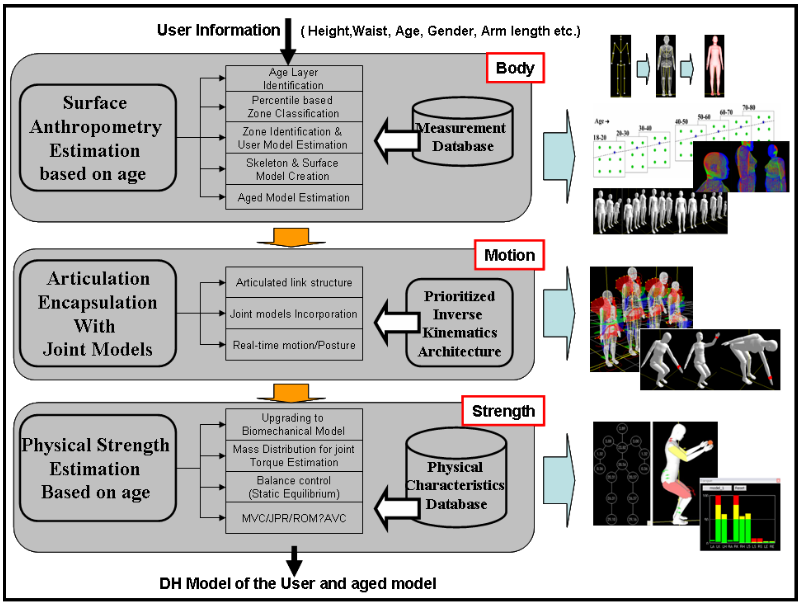


Figure 2. Abstract overview of creating a digital model of the user

Body : 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/) 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. 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 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 3].

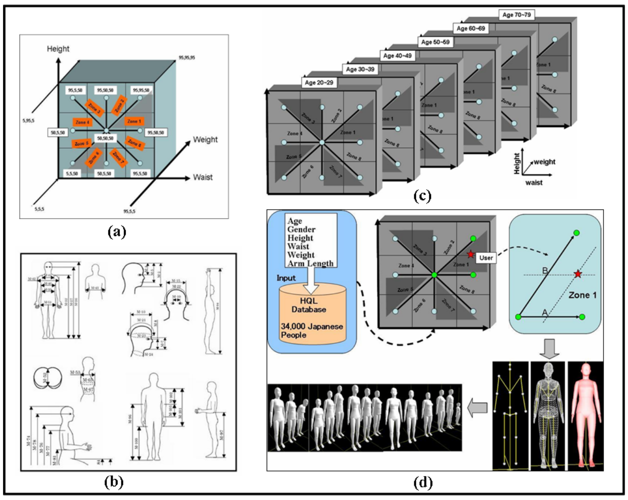


Figure 3. Method of creating User-Model from a Database of 34000 Japanese people a) age layer creation b) measurements in the Databse c) age groups d) User-extraction method

Motion: The motion of digital human is entirely controlled by a hierarchically articulated structure. We use H-Anim standard [Seitz, 2005] 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 [Baerlocher, Boulic, 2004][Hareesh et al, 2005].Using the developed system, even a non-specialist user can control anthropometric digital human postures intuitively in real time [Fig 4]

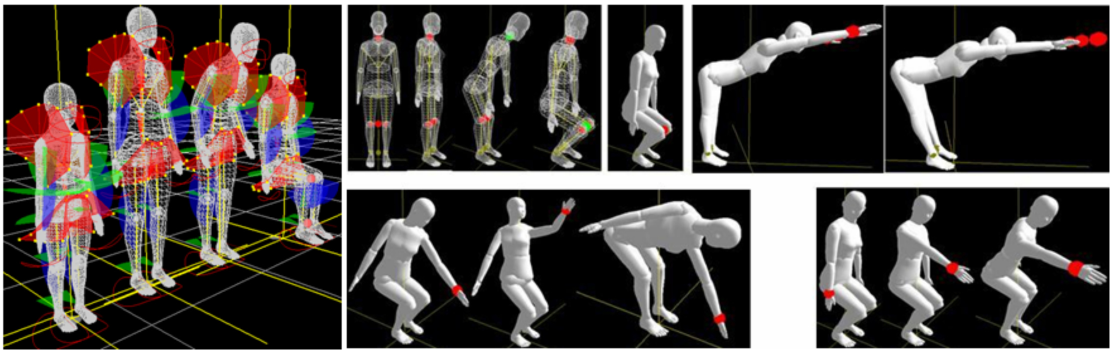


Figure 4. Joint model encapsulation and Real-time Motion control using prioritized Inverse Kinematics Architecture

Strength: 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.

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 [Chaffin et al] 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 carried out a quantitative analysis to strength estimation by making use of a physical characteristic database of actual human subjects. Analysis included the estimation of three variables based on age and they are 1) Maximaum Voluntary Contraction (MVC) 2) Joint Passive Resistance (JPR) and 3) Affordable Voluntary Contraction (AVC). The strategy for determining the strength estimation is explained in the Figure 5

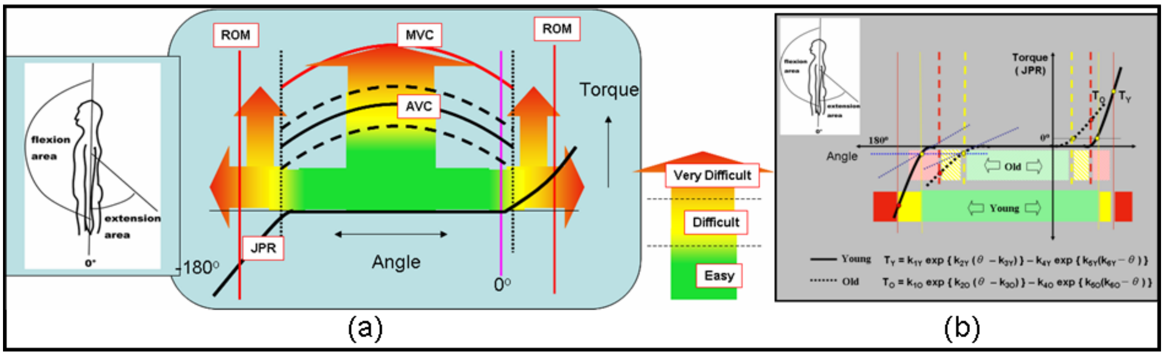
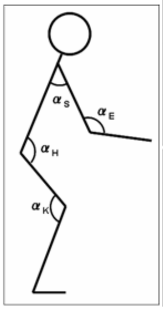


Figure 5. Strength Estimation Strategy plan a) MVC and AVC b) JPR

The strength is being estimated by using a database developed by National Institute of Technology and Evaluation and is publicly available since 2002. 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 a new aging algorithm for predicting the mean Joint moment strength for different ages has been quantitatively estimated by identifying age factor coefficients (AF) for each age group [Hareesh 2010]. Figure 6 shows the modified mean strength equations corrected for different age groups.

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



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

Figure 6. Mean strength aging equations and Age correction coefficients (AF) for both genders

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%

Figure 7. Snapshots of the method of estimating AVC using biodex system (left) and the estimated AVC values as a percentage of MVC with SD (right)

To estimate affordable voluntary contraction (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 [see Figure 7]

2.2 Functions to create 3D product model (using primitive geometries) from 2d images/drawing

To create 3D product model from a 2d image or a photo, functions have been developed and incorporated in to the total system. Using front view, side view and top view it is possible to create an approximate 3D model using primitive polygon models and texture mapping. Figure 8 shows the snapshots of creating a wash basin from 2D image. Instead of creating 2D images, designers could directly select the appropriate template model for editing in the 3D world also. An intuitive interface to edit this templates also being made so that even a naïve user can edit the model using simple mouse operation.

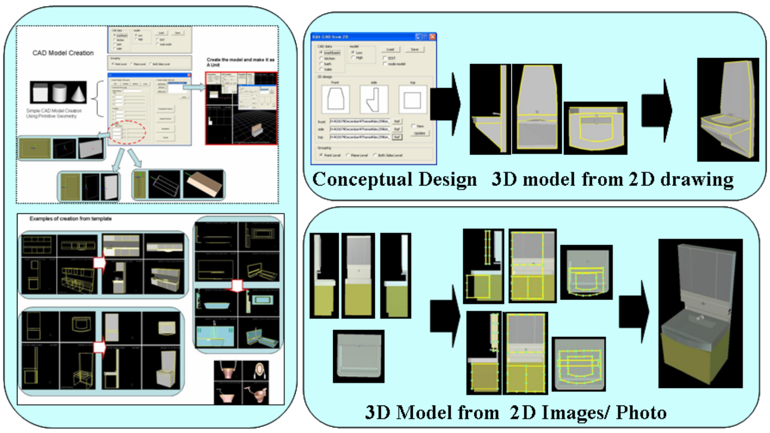


Figure 8. Overview of creating 3D object model from 2D images

3. Total System as an Ergonomic Evaluation Engine

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

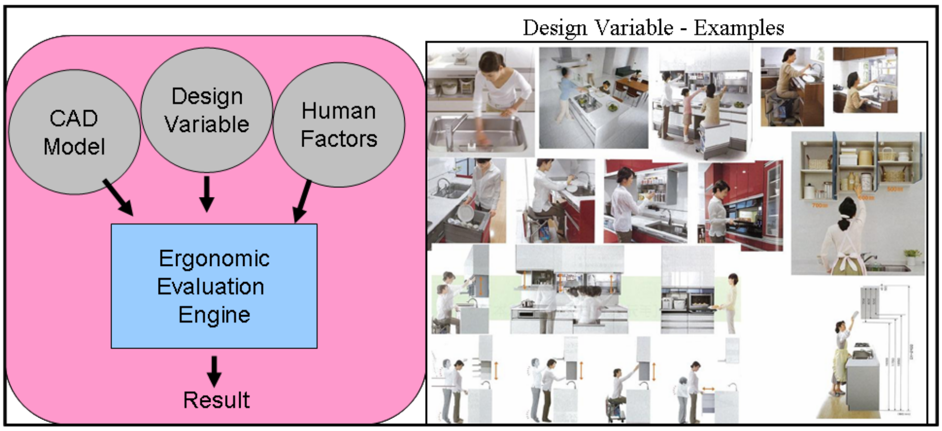


Figure 9. Abstract overview of the usage of the developed system as an evaluation Engine

Design variables are very 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 analyze the permissible height of the handle for the selected population. Where as 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.

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				

Figure 10. Strategy table to catogerize the design variables and Human factor

Figure 9 shows the glimpse of the design variables in the context of this paper and the method of defining the design variables are shown in Figure 10. 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 peroformance measure which could be physical limits, joint torques and perception.
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 a simple to use interface has been developed such that user could set the direction using arrow marks as shown in figure 11.
To link user-model with design variable, we have created generic functions to move an object with digital humans, to set up a trajectory for the moving objects etc. Figure 11 shows a couple of snapshots.

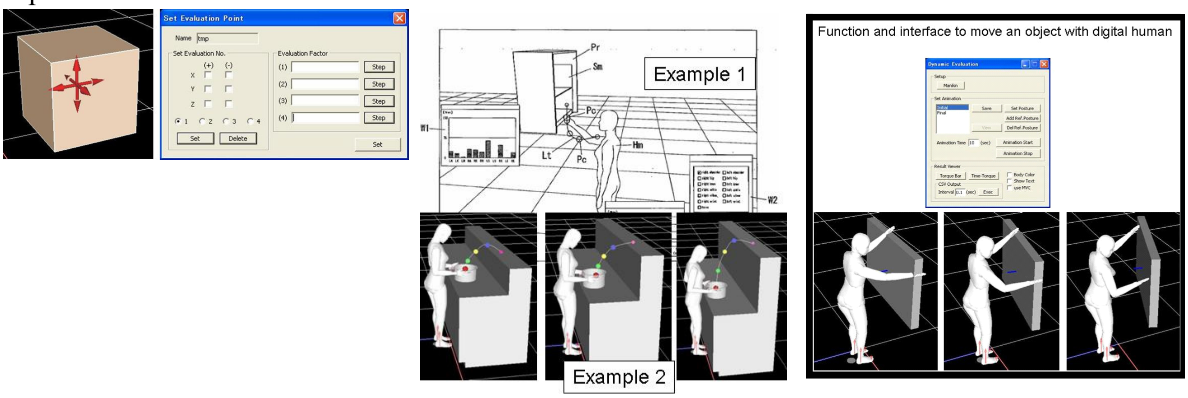


Figure 11. Interface functions between User-Model and Product Model

To understand the usage and advantage of the developed system as an evaluation engine shown below are a few case studies that we have conducted.

3.1 An Ergonomic Approach to estimate the trajectory of a Pull-down Shelf

Focused application is as shown in the figure 12, a pull-down shelf of a kitchen. In the context of designing a Universal design kitchen shelf, constraints for the design criteria were defined as the followingg.

1. The height of the shelf- handle 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" should not have the feel of fear when the shelf comes towards the user

Primary Design Variables (mult-mode)

Optimal trajectory estimation for the pull-down shelf

Secondary Design Variables

Weight of the Shelf (1kg ～10kg)

Human Factors

Target User : Young / Old
height : 1.5m ～1.8 m
Weight : 50 kg ～70 kg
Action : Push/pull of the shelf (one hand / both hand)
Posture : normal/ one leg forward
Performance measure : Joint torque

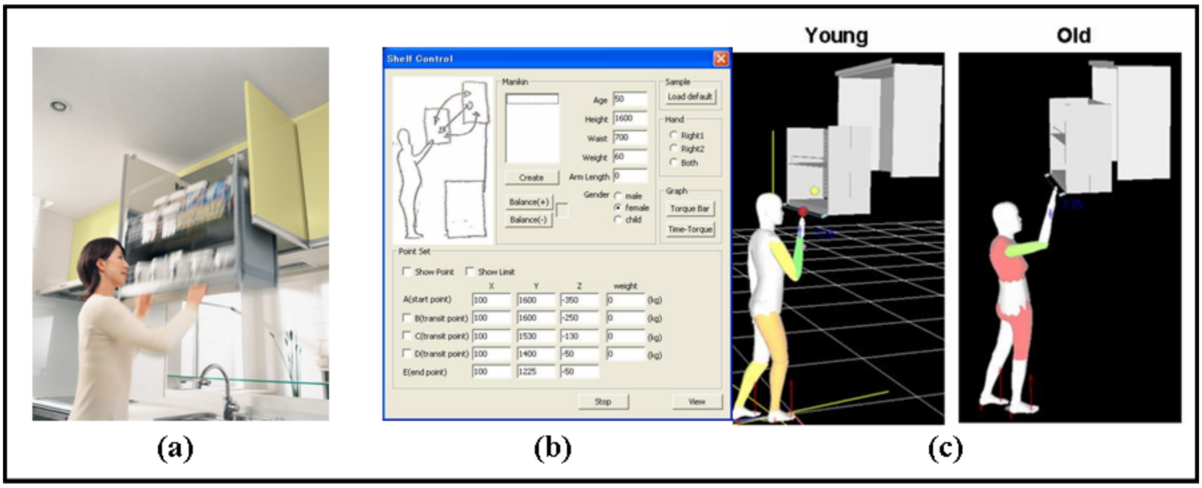


Figure 12 Method to estimate the trajectory of a pull-down shelf

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. It is found that the diagonal trajectory is the optimal solution for a wide range of population.

3.2 Counter and Sub-counter Height and Depth Estimation of Kitchen

The goal of the simulation was to determine the approximate range of values for the counter width and sub-counter height, such that the system is affordable by a heterogenous population with differing abilities. Towards the estimation, the design variables are set up as the following

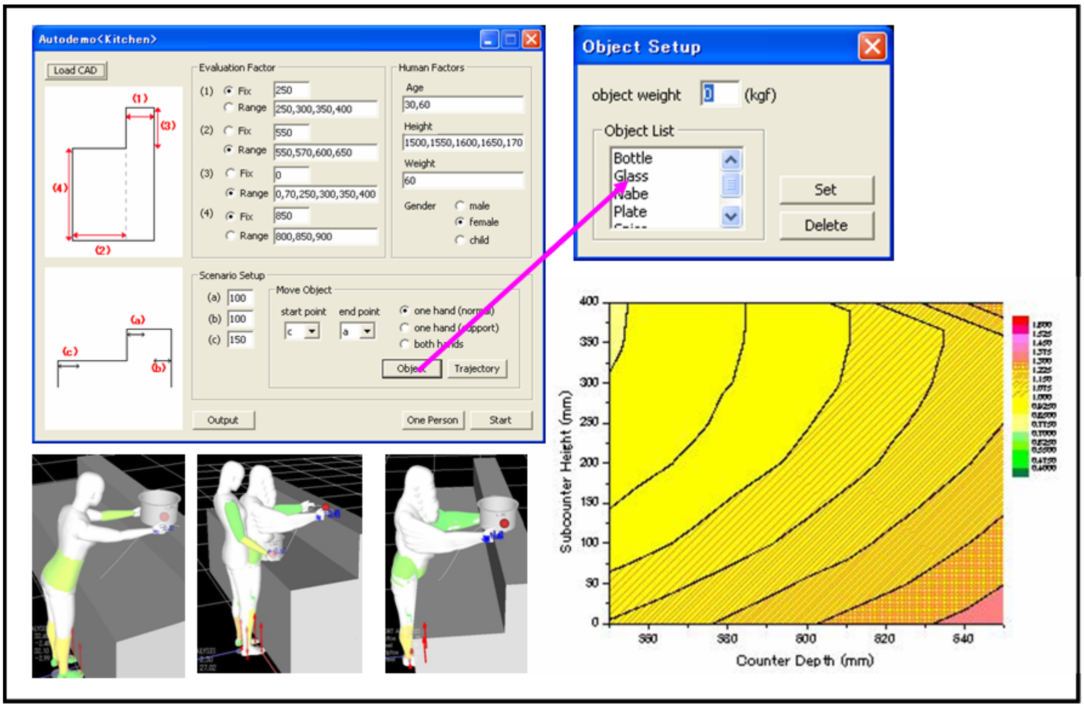


Figure 13. Method to estimate the counter and sub-counter height of a UD Kitchen

Primary Design Variables (mult-mode)

Counter Width and Sub-Counter height

Secondary Design Variables

Move an object of a specified weight from “c” to “a” (for the defined values of C and A) Please see the GUI in [Fig.13] to know about a,b and c

Human Factors

Target User
height : 1.4m ～1.8 m
Weight : 50 kg ～70 kg
Age : 30 ～70
Action : Move object from C to A （using one hand or both hand)
Performance measure : Joint torque

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 were successfully estimated. The contour graphs [see Figure 13] shows the affordable values with green and yellow

3.3 Wash basin Analysis

Figure 14 shows another couple of examples regarding wash basin analysis. In the 1st case, the aim was to determine the range of affordable values for bowl width and the distance of faucet from the wall such that the head of the human will not collide with the mirror . In the 2nd case, the aim was to design a universal wash basin

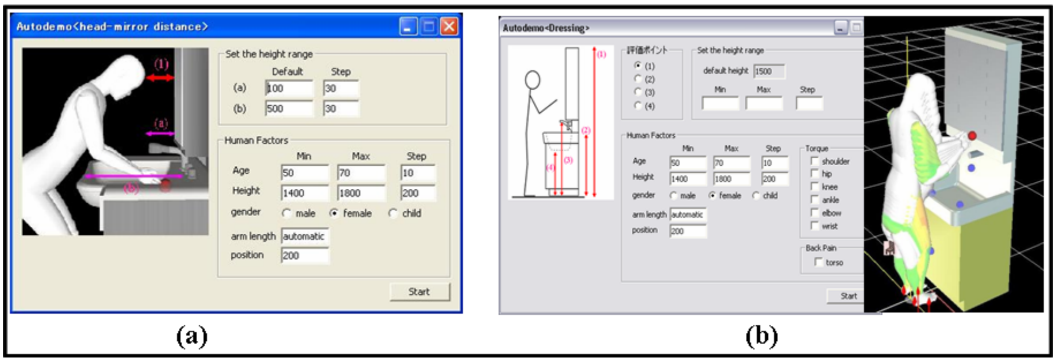


Figure 14. Method to identify the permissible range of values of design variables of wash-basin Snapshots of other developed application examples

Figure 15. Some examples to demonstrate the usage of the developed system as an ergonomic tool at the conceptual design stages of various products

4. 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. 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.

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