CAD System for Human-Centered Design

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ABSTRACT

Severe competition in today's marketplace has imposed additional demands on the products being sold. In addition to basic requirements, such as function, quality, price, and appearance, modern products must be increasingly comfortable and easy to use. The current discussion will introduce two fundamental approaches intended to improve the comfort and user-friendliness of new products. The first approach involves designing a product to reflect the geometry of the human body. This approach can be exploited when designing custom-tailored products, such as shoes, clothes, and helmets. Specialized CAD systems for custom tailoring these products will be introduced together with human body scanners and human body modelers. The other approach is to design a product based on the simulation of both product behavior and human motion. This approach can be used to design products that are used in close association with the human body to maximize its comfort and ease of use. To realize the simulation environment, a CAD system that allows modeling the human and the product in the same environment and provides the simulation results is necessary. In this paper, a prototype CAD system for this purpose is also introduced.

Keywords: Human-Centered Design, CAD, custom-tailoring, human motion simulation

1. INTRODUCTION

Due to globalization and increasingly competitive market environments, modern products must meet more requirements than ever before. They must not only be functional and aesthetically pleasing, but comfortable and ergonomic, as well. Consumers increasingly demand products that conform to the human body in a customized way in order to maximize comfort and mitigate user fatigue. Similar design elements are also becoming apparent in the design and layout of factory spaces. It is now common for factories to adopt new ergonomic designs in order to reduce the possibility of dangerous situation and to increase the efficiency of interactions between workers and machines. These types of design that consider the static geometry or dynamic responses of the human body are referred to as 'human-centered design'.

Current CAD systems are unable to fully support a human-centered product design. Most of the research regarding ergonomic design has primarily focused on simple geometric analysis and simulation and has considered only the human model rather than the interaction between the product and the human model. As a result, it is difficult to apply the method to the traditional design process. Consequently, such designs must be completed manually using trial-and-error iterative experiments on physical prototypes.

Some integrated CAD systems, such as CATIA from Dassault Systems, provide simple simulation and analysis tools for the human body, such as HBR (Human Builder), HME (Human Measurement Editor), HPA (Human Posture Analysis), and HAA (Human Activity Analysis). However, the functions and capabilities of these internal modules or add-ons are quite limited when compared to that of dedicated human simulation tools [3]. Particularly, the human analysis process in CATIA can only be used for static analysis, and not for dynamic analysis. Recently, many applications to simulate the human motion and the corresponding muscle reactions have been developed. These tools are very useful for simulating the man-machine behavior simultaneously. Furthermore, some commercial software, such as SIMM from Motion Analysis Company and LifeMOD from Biomechanics Research Group, have been designed for this purpose [12][20]. However, these software packages were developed considering only the human motion simulation and did not provide the design environment for the products which interact with the human motion. They also do not provide an easy way to define the interaction between the human and the product and to run the simulation for both the human and the product.

Due to the aforementioned limitations, the design of human-friendly products primarily involves trial-and-error. This trial-and-error process is undesirable because it inherently requires human operators and their subjective evaluations. Accordingly, an integrated approach combining the CAD/CAE system and human simulation tools is strongly recommended. Also, an in-depth study of the interaction conditions between the human body and product model is required. In order to achieve the goal of human-centered design, the following research activities must be conducted:

- Human body modeling.
- Human motion and muscle force simulation.
- Design environment for modeling both human body and product.

The related works on the first two topics in the above list will be described in the following chapters, and then the third topic will be demonstrated with several case studies performed at the Seoul National University.

2. HUMAN BODY MODELING

The human models used for human-centered design can be classified into four categories: simple geometric models, multi-body models, finite element models, and a hybrid models that combine multi-body and finite element models.

2.1 Simple Geometric Model

Simple geometric models of the human body are often used to design custom-tailored products, to perform simple ergonomic analysis for applications like reach evaluation, and to create animations. Geometric models of the whole human body or the portions thereof are obtained by scanners or section data from computer tomography or laser bean scanners. The scanned data are usually triangulated and the anatomical features are represented as a facet model.

2.2 Multi-body Models

The musculoskeletal systems of a human body are usually modeled as a set of rigid bones connected by joints. These joints include muscle-tendon actuators that span the joints and develop force, thus generating moments about the joints. These models allow passive simulation as well as active simulation (inverse and forward dynamics). Multi-body models can be used in impact simulation and analysis, ergonomics, comfort study, biomechanical analysis, movement simulation and analysis, and surgical planning.

MADYMO [14] provides a series of multi-body models whose geometries are represented by ellipsoids or facet surfaces. LifeModeler [12], developed by the Biomechanics Research Group, is another commercially available human motion simulation program that uses ADAMS (Automatic Dynamic Analysis of Mechanical Systems) as a dynamics solver. It provides a default multi-body model of the human body that can be modified by changing anthropometric sizes. Simulation examples using LifeModeler will be illustrated in Section 3. Another commercially available software known as AnyBody [1] is similar to LifeModeler, in that it provides the simulation of the human body motion with the human body stored in the program.

The Neuromuscular Biomechanics Lab (http://www.stanford.edu/group/nmbl/) at Stanford University created a software package called SIMM (Software for Interactive Musculoskeletal Modeling). This software enables users to develop, alter, and evaluate models of musculoskeletal structures. In SIMM, a musculoskeletal model consists of a set of body segments that are connected by joints. The joints are modeled using detailed, accurate kinematics functions, or simple pin or ball-and-socket joints. The model includes muscle-tendon actuators that span the joints and develop force, thus generating moments about the joints. This software can be used for biomechanical analysis, movement analysis, surgical planning, and ergonomics.

2.3 Finite Element Models

Finite element models of a whole human body, or portions thereof, can be used to evaluate the effects of a product on the human body during use.

2.3.1 WSU model

The Wayne State University (WSU) Bioengineering Center (http://ttb.eng.wayne.edu) is among the pioneers in human modeling. The WSU Human Injury Investigation Model was developed for use with simulation programs such as MADYMO, LS-DYNA [13] and PAM-CRASH [19].

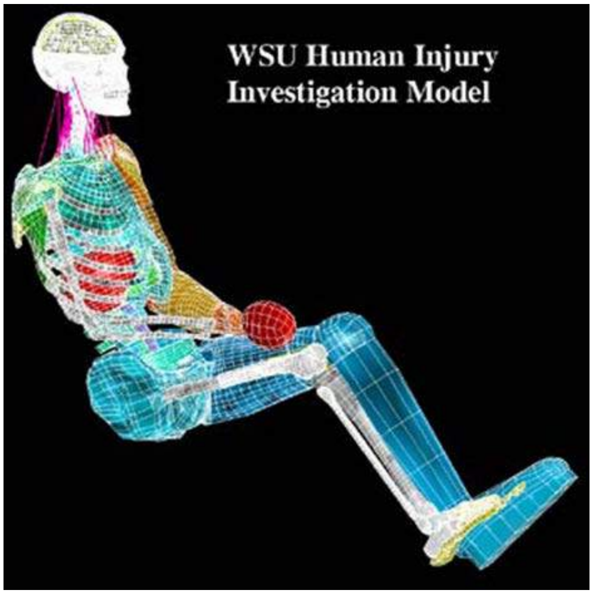


Fig. 1. WSU model.

The WSU Bioengineering Center also determined a unique data set to simulate head impact. The data set contained a geometric mesh which described all the components of the head, including the scalp, skull, inner brain membranes, and hemispheres of the brain, cerebellum, brain stem, ventricles, cerebrospinal fluid, and bridging veins. All of these components were made up of 38,000 elements and 29,000 nodes. They also developed finite element models of other portions of a human body, such as head and neck, thorax, abdomen, spine, pelvis and hip, and knee.

2.3.2 HUMOS-1 & HUMOS-2

HUMOS is full human body model that was funded by the EU and developed by a consortium of European car companies, research institutes, universities and software vendors.
HUMOS-1 shown in Fig. 2 is a human model of a male in a driving position close to the 50th percentile [2].

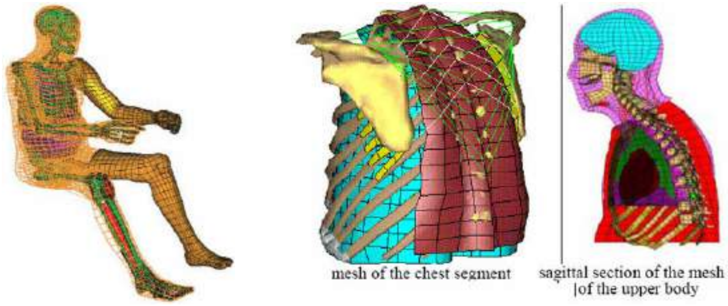


Fig. 2. HUMOS-1 model.

HUMOS-2 models [24] are the successor of HUMOS-1 models. They also provide the positioning tool to put the human models in a proper pose for each specific application.

2.3.3 THUMS

THUMS (Total Human Model for Safety) is a family of human models developed by Toyota Central R&D Labs (http://www.tytlabs.co.jp/eindex.html) and are illustrated in Fig. 3.

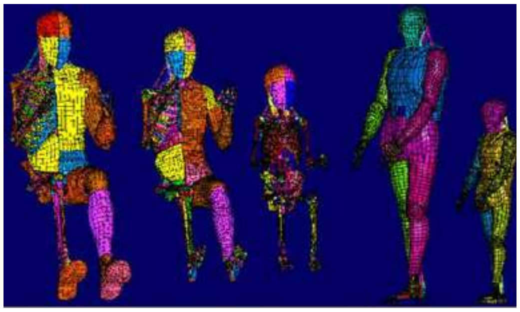


Fig. 3. THUMS Human Model Family: AM 50, AF50, AF05, 6 year old child, pedestrian and a girl.

Each model contains more than 80,000 finite elements and 60,000 nodes [18]. THUMS also provides a brain model to simulate a brain injury.

2.3.4 H-Models

The H-Model family was developed at the Hong-ik University in Korea with the IPSI/ESI partner companies for impact biomechanics, pedestrian impact and riding comfort.

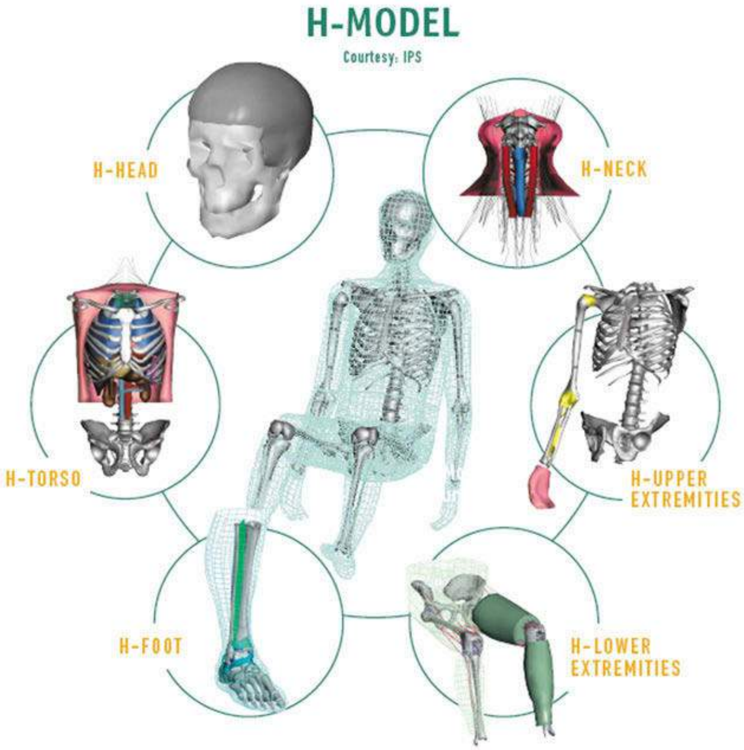


Fig. 4. Elements of the H-Model.

2.4 Hybrid Model

Sometimes, finite element models require too many calculations and the associated simulation may not serve as a good design tool. In this case, hybrid models that combine rigid bodies and finite elements are used.

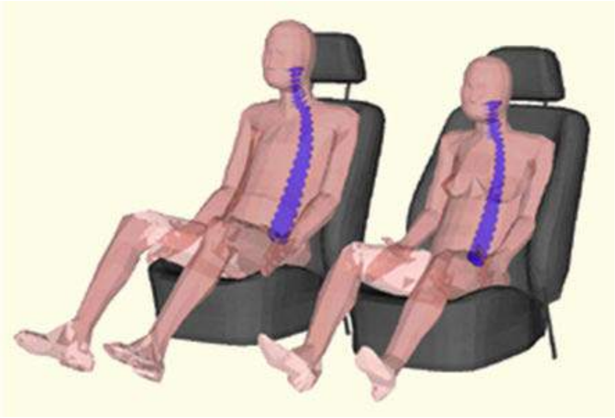


Fig. 5. Hybrid models that are mixtures of rigid bodies and finite elements.

Fig. 5. shows an example of a hybrid model where rigid bodies are used for most segments, but a deformable structure is used for the thorax.

3. HUMAN MOTIOIN AND MUSCLE FORCE SIMULATION

As mentioned in the previous section, there are many commercially available simulation software products, such as LifeModeler, MADYMO, AnyBody, and SIMM. These all basically provide generic models for the human body and allow the user to scale the human model, position it to the same position as that in operation, and solve the dynamic equation by rigid dynamics solver or finite element analysis code. The results of the simulation are the human motion, forces exerted by the muscles, and the stresses or strains at the desired location of the human body. From these results, the comfort or ease of operation can be estimated for a given task. Figures 6-9 illustrate the example output of some simulations.

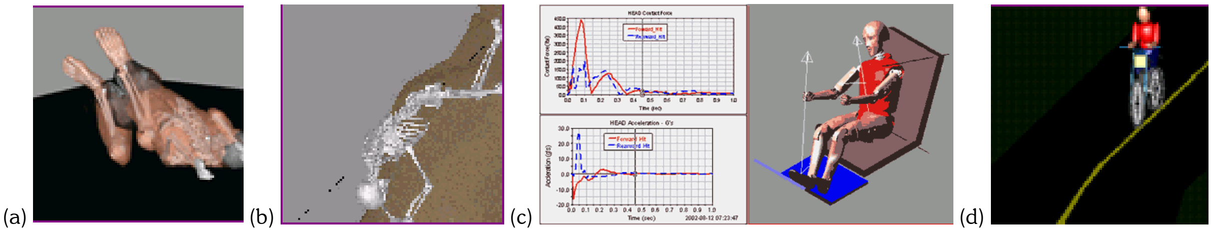


Fig. 6. Injury simulations: (a) Falling, (b) Bungee jumping, (c) Car crash and (d) Motorcycle crash.

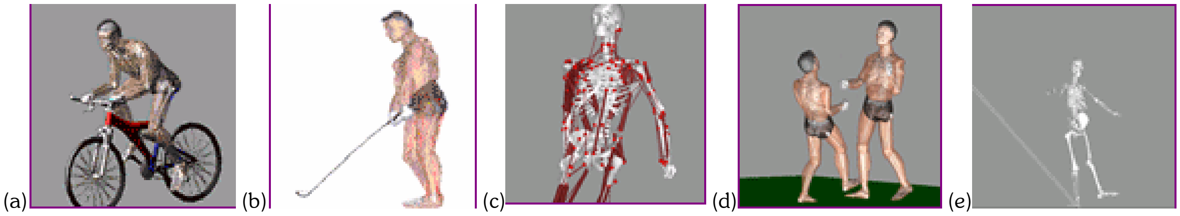


Fig. 7. Performance: (a) Bicycle riding, (b) Golfing, (c) Exercise, (d) Fighting and (e) Dancing.

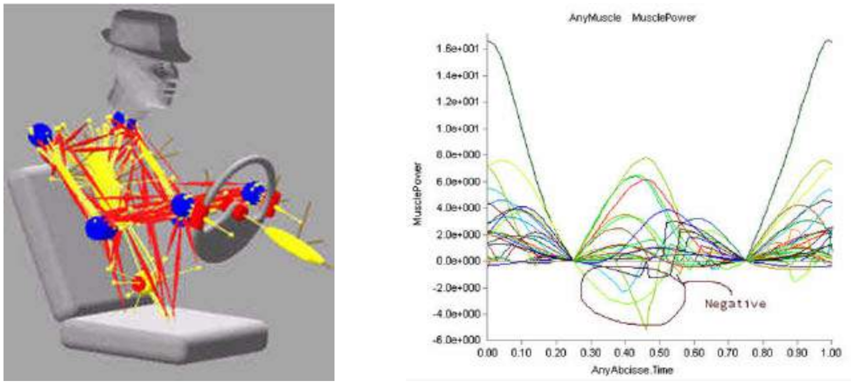


Fig. 8. Optimizer: Car driver muscle works.

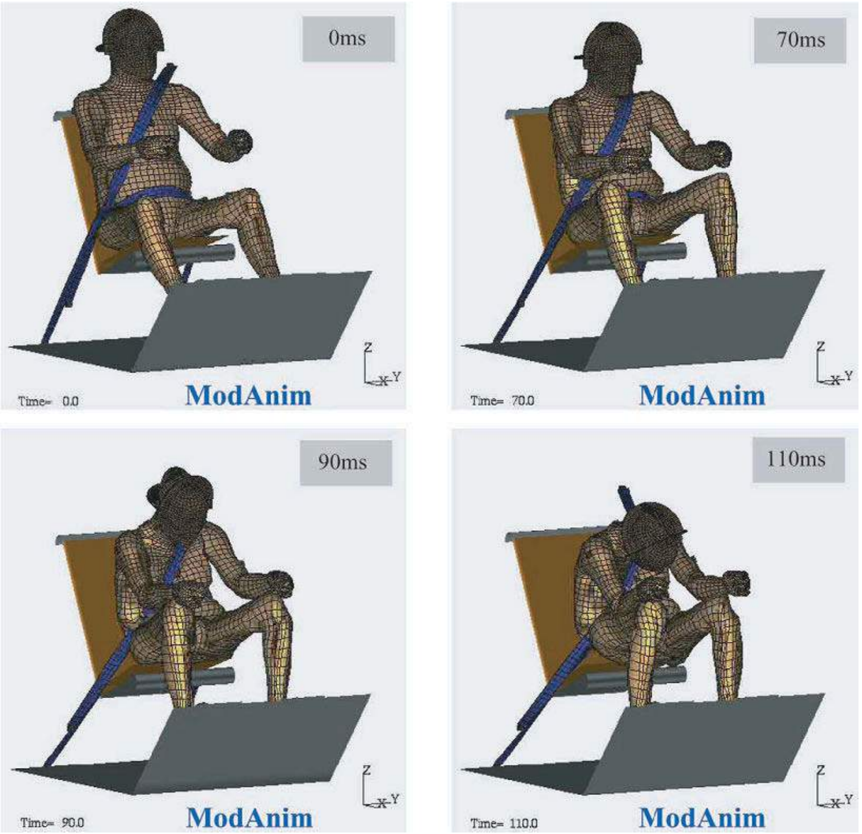


Fig. 9. Impact simulation with a belt system.

4. CASE STUDY 1 - CUSTOM TAILORING PRODUCTS USING HUMAN MODEL

As the standard of living continues to improve, consumers tend to purchase products that are custom tailored to fit their bodies perfectly. Many CAD systems for custom tailoring products are currently being developed to meet this growing need. In this presentation, two examples of custom production systems developed at Seoul National University are introduced: custom tailoring systems for shoes and for wigs.

4.1 Custom Tailoring Shoes

We implemented the shoelast design system as part of a system to create custom tailored shoes. The shoelast design system uses the scanned data from the foot scanner to design a new shoelast fitted to the scanned data.

The proposed shoe last design system consists of three parts. In the first part, the pre-processor, the point cloud data from the scanner is converted to a data format that is easy to handle. An existing shoelast that is closest to the scanned foot is selected from the database and is modified to fit to the customer's foot. At the same time, a customized insole is also designed so that its surface exactly fits the bottom of the foot. The post-processor then generates the tool path data for manufacturing the shoelast and the insole. Figures 10-16 illustrate the result of each step.

Fig. 10. Foot scanner.

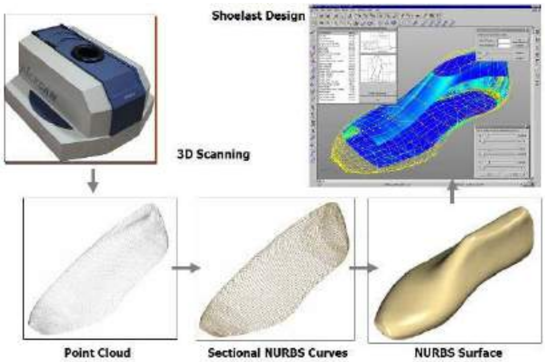
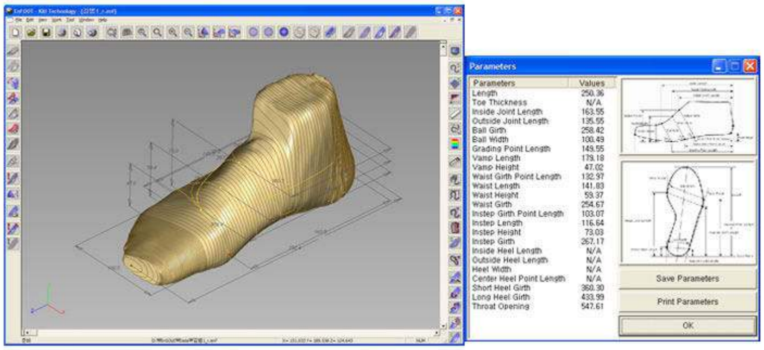
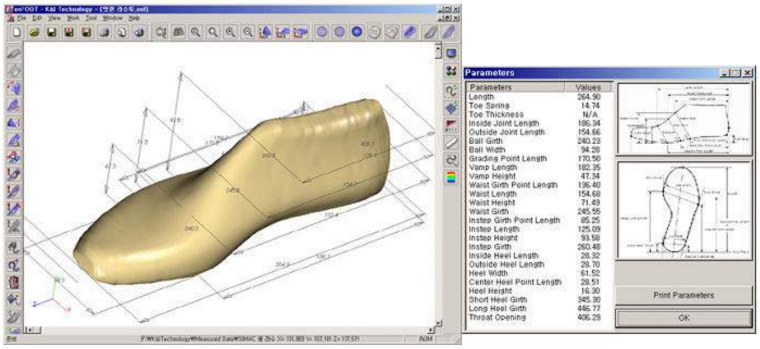


Fig. 11. Scanned result.



Parameters	Values
Length	250.36
Toe Thickness	N/A
Inside Joint Length	163.55
Outside Joint Length	135.55
Ball Girth	258.42
Ball Width	100.49
Grading Point Length	149.55
Vamp Length	179.18
Vamp Height	47.02
Waist Girth Point Length	132.97
Waist Length	141.83
Waist Height	59.37
Waist Girth	254.67
Instep Girth Point Length	103.07
Instep Length	116.64
Instep Height	73.03
Instep Girth	267.17
Inside Heel Length	N/A
Outside Heel Length	N/A
Heel Width	N/A
Center Heel Point Length	N/A
Short Heel Girth	360.30
Long Heel Girth	433.99
Throat Opening	547.61

Fig. 12. The parameters of foot.



Parameters	Values
Length	264.90
Toe Spring	14.74
Toe Thickness	N/A
Inside Joint Length	186.34
Outside Joint Length	154.66
Ball Girth	240.23
Ball Width	94.28
Grading Point Length	170.50
Vamp Length	182.35
Vamp Height	47.34
Waist Girth Point Length	136.40
Waist Length	154.68
Waist Height	71.49
Waist Girth	245.55
Instep Girth Point Length	85.25
Instep Length	125.09
Instep Height	93.58
Instep Girth	260.48
Inside Heel Length	28.32
Outside Heel Length	28.70
Heel Width	61.52
Center Heel Point Length	28.51
Heel Height	16.30
Short Heel Girth	345.30
Long Heel Girth	446.77
Throat Opening	406.29

Fig. 13. The parameters of standard shoelast.

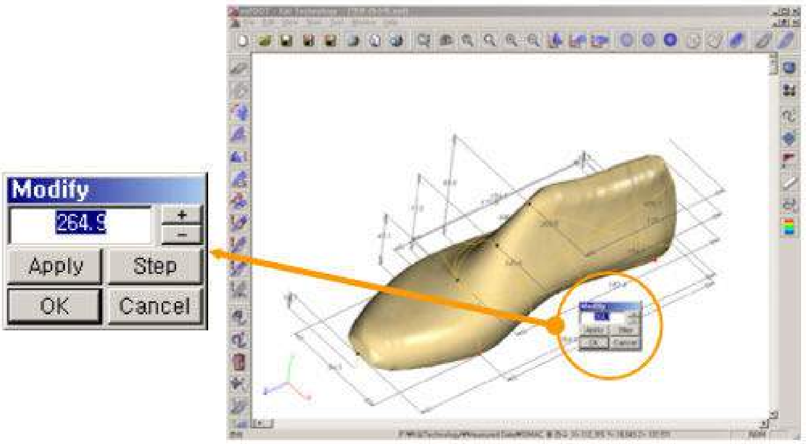


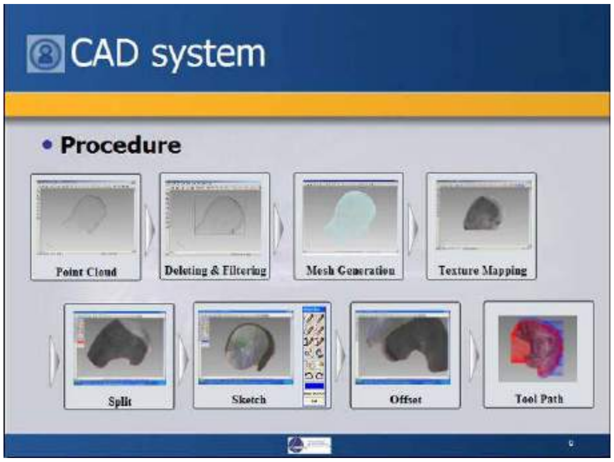
Fig. 14. The modified shoelast.

Fig. 15. The machined shoelast.

Fig. 16. The machined insole.

4.2 Custom Tailoring Wigs

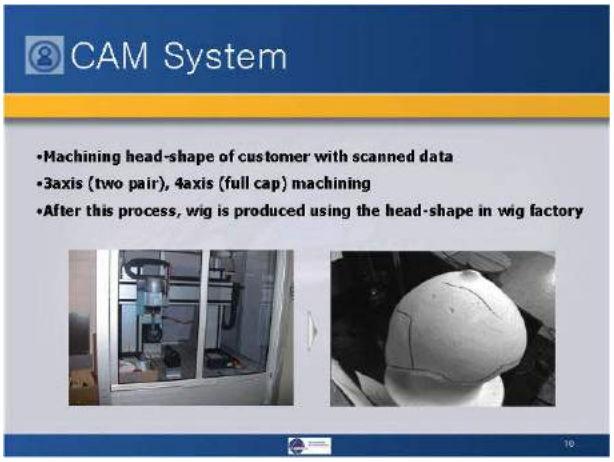
A customized wig manufacturing system was based on the same concept as the customized shoe manufacturing system. The head is scanned in order to generate a net, on which hairs are implanted. Since the net has the same shape as the head while the shape of the shoelast differs from that of the foot, the development of customized wigs will be inherently easier than for shoes. Figures 17-18 show the general procedure.



CAD system

- **Procedure**

Fig. 17. Procedure of custom tailoring wigs.



CAM System

- Machining head-shape of customer with scanned data
- 3axis (two pair), 4axis (full cap) machining
- After this process, wig is produced using the head-shape in wig factory

Fig. 18. CAM system for customized wig manufacturing.

5. CASE STUDY 2 - PRODUCT DESIGN CONSIDERING EFFECT ON HUMAN OPERATOR

As stated in the previous sections, many commercial programs already exist to simulate the human body and muscle forces for a given motion. However, traditional biomechanical research has largely focused on human modeling and analysis, has largely ignored the design of the product. For example, many attempts have been made to estimate the optimal pedaling rate or direction while cycling [4],[15-17][22]; however, relatively little effort has been expended in order to determine the optimal position of the crank with respect to the saddle when the size and posture of the human model are changed [11]. This is similar to past situations in which CAD and FEA systems were run independently on different platforms. These days, we run FEA inside CAD systems, and the design alteration is performed based on the FEA results right in the design stage.

Jung and Kee suggested an integrated design framework for ergonomic product design [6]. A new man-machine interface model is proposed to integrate the ergonomic evaluation tools into the CAD system; the visibility and reach functions are used for the ergonomic evaluation function. The systematic scenario is quite similar to this study. They modeled the human body as a multi-link system and used the Denavit—Hartenberg notation of robotics for the kinematic representation. However, their system can handle only the evaluation of visibility and reach functions. Also, the geometry of the human model is represented by the boundary-representation (B-rep), and its main function is only to graphically visualize the human body. Therefore, it cannot be directly used as design references. Finally, there is no specific interface relation or constraint between the human body and solid objects.

Sooyeup Lee tried to determine the objective function value of the motion of various bicycle models operated by a musculo-skeleton human model in a computer's virtual space [11]. By minimizing the value of this objective function the muscle can exercise with minimal force, leading to minimum muscle exhaustion. His research represents an ideal approach to determine the important design parameters in the product model. However, the approach is limited to the pedaling motion of bicycles and the total computing time is very long. Consequently, a more general approach to enable human-centered design in the conventional design process is needed.

In this case study, we propose a new design platform that is constructed upon commercial CAD systems. The human body and product are closely interrelated by certain combinations of interactions defined in the platform. A product design can be evaluated for many representative human bodies without re-defining the relationships between them. The integrated platform is developed to have the following features.

- General Feature-based CAD capabilities.
- Input of human model into the platform.
- Interactive specification of human-product interaction [21].
- Automatic inverse kinematics on the human body model for the initial posture determination from the human-product interaction [5][7-10][23],[25].
- Import motion data from motion capture camera.
- Generation of input file for human motion simulation program.
- Graphic postprocessor to display the results of human motion simulation.

In this case study, the integrated platform was constructed on a commercially available CAD system and the features listed above were included as add-on programs, as shown in Fig. 19.

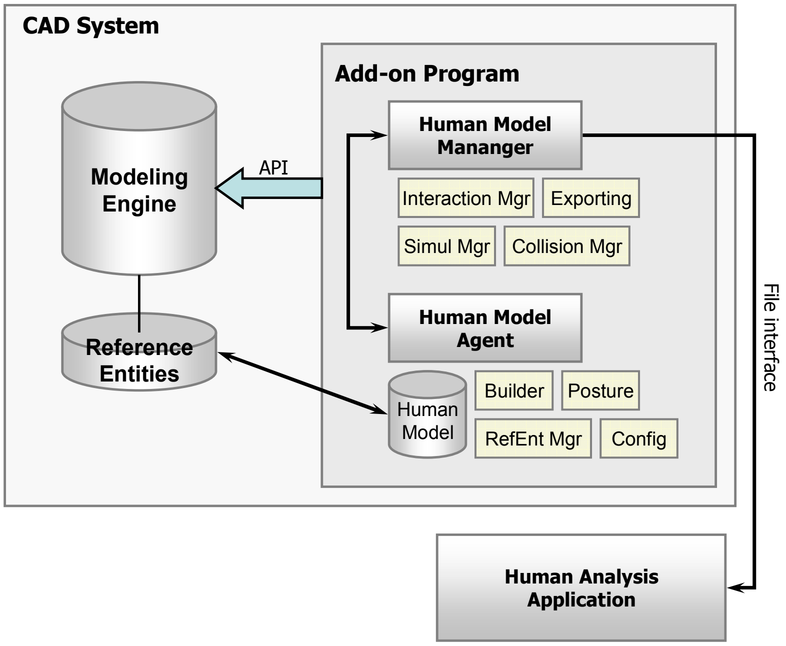


Fig. 19. Overview of the proposed system.

With the help of the "Human Model Agent" and "Human Model Manager" modules, the user can handle the human model and the interaction information in an integrated design environment. Furthermore, the user can easily run the simple kinematics simulation, evaluate the motion envelope of the human body, and compare the results for the different human models.

For the detailed dynamics simulation and analysis, "Human Model Manager" modules can create the batch command file for the external simulation software. All the time-consuming and iterative steps can be minimized.

The HMA (Human Model Agent) and HMM (Human Model Manager) were implemented as add-on programs for SolidWorks 2005. We also used the BRG.LifeMOD Biomechanics Modeler from the Biomechanics Research Group, as the human motion analysis software. This software is based on the popular ADAMS software product.

Interaction Type	
Attachment(with A and B)	'bushing' force conditions
Possibly Contact(with A and B)	'contact' force condition
Fix(with A and B)	'fix' conditions
Hand-holding	
Stepping-on	
Sitting-on	
Lean-against	
Lift an object in arms	

Tab. 1. Classification of interactions between human model and product model.

In this case study, we classified the interactions between the human and product models into 8 categories (shown in Tab. 1), depending on their postural meaning and interaction characteristics. With these interaction types, the posture of a human body is more easily specified compared to when we use LifeModeler or other simulation programs.

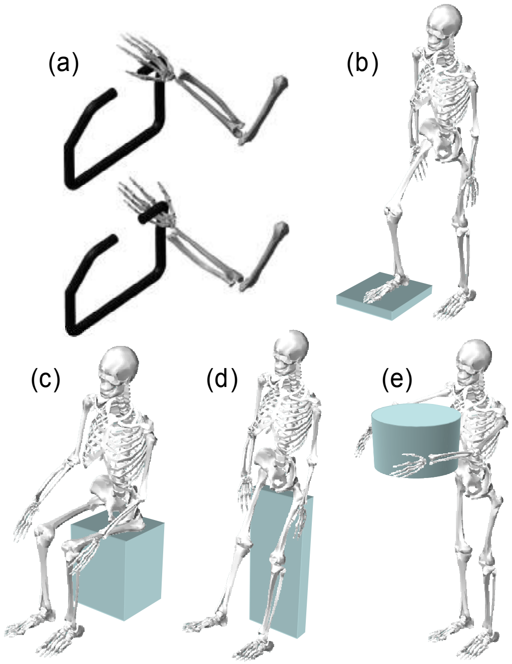


Fig. 20. (a) Hand-holding (pronation, supination), (b) Stepping-on (with right foot), (c) Sitting-on, (d) Leaning-against and (e) Lift an object in arms.

Each interaction type can be modeled differently upon user input. For example, the 'stepping-on Object A with left foot' interaction can be modeled as the 'bushing' model or 'contact' model with different parameters, Fig. 20.

'Attachment', 'Possibly Contact', and 'Fix' are the same as the 'bushing' force, 'contact' force, and 'fix' condition, respectively. The other 5 interactions have more postural meaning and interaction characteristics, but they are internally expressed as one of the 'Attachment', 'Possibly Contact', or 'Fix'.

When these interactions are assigned, the posture of the human model is also adjusted for the postural meaning of the interaction. It is very easy to model the interaction between the human model and product model because assigning the interaction also changes the human posture automatically.

5.1 Home Fitness Cycling Machine

In this example, we will examine the effect of the height of the saddle on the motion of the human body. For the two different positions of the saddle, the bio-mechanic analysis is performed, and the results are compared to each other.

We first use the proposed system to model the human and bicycle in the normal saddle position (Fig. 21). We then run the simulation in LifeMOD with the exported files from the system. The simulation result is shown in Fig. 22.

Subsequently, we alter the position of the saddle in the cycle machine. If we move the saddle part downward, the human model is automatically repositioned. Finally, we get the modified exported files.

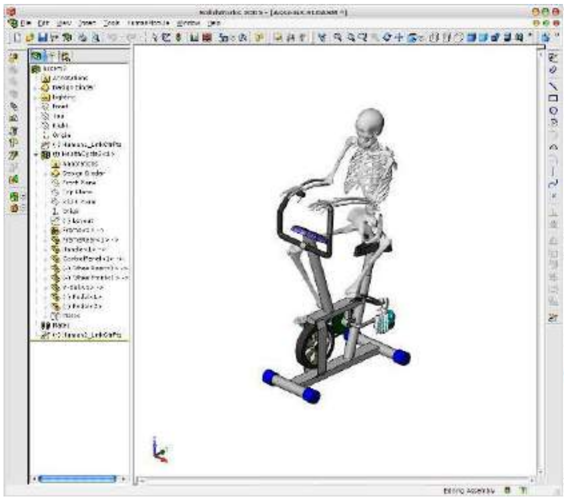


Fig. 21. Modeling example using proposed system.

Fig. 22. Result of simulation (10 selected frames).

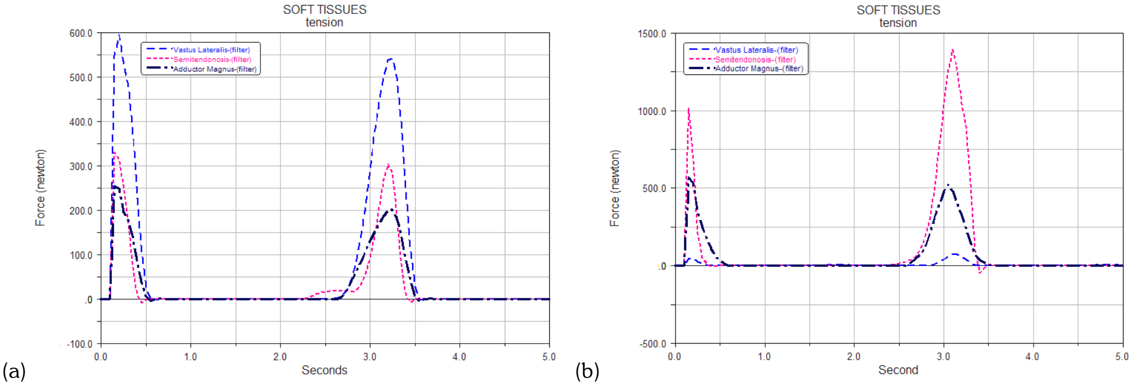


Fig. 23. Comparison between 2-different saddle positions.

The result can be quantitatively compared by selecting a few representative muscle forces during the simulation (5.0 sec, 100 time-steps) and plotting them in Fig. 23.

For the normal saddle position, the maximum force for all muscles is smaller than 600N (Fig. 23(a).). However, for the low saddle position, the maximum force is greater than 1400N (Fig. 23(b).).

The result of the simulation is consistent with our own experience. When we ride on the small bicycle (such as a child's bicycle), pushing the pedals is difficult because there is a very small free region of movement.

5.2 Elliptical Trainer

The second example involves another fitness machine frequently referred to as an Elliptical Trainer. The overall combined motion of this product and the human model is quite complex. As a result, it is difficult to estimate the human motion in this example, even for an average person. The interactions and stabilizing constraints are assigned as shown in Fig. 24.

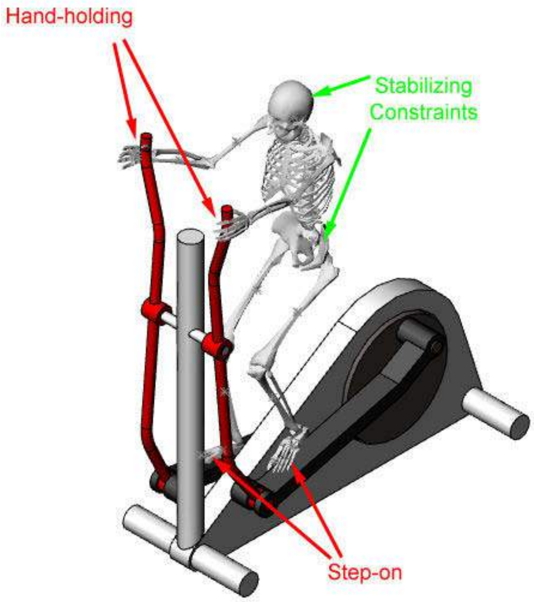


Fig. 24. Assigning of interactions and stabilizing constraints.

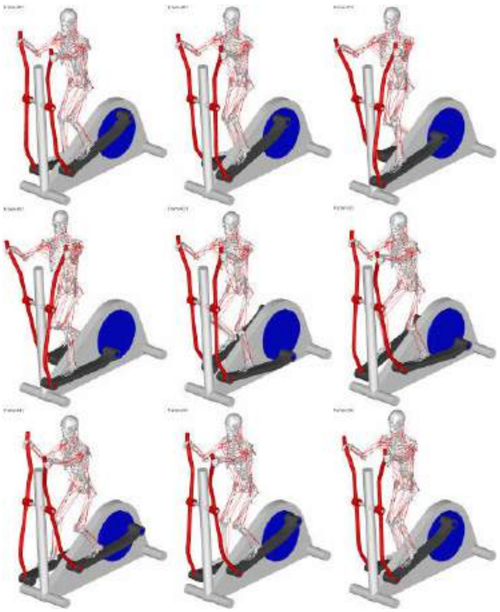


Fig. 25. Simulation result of elliptical trainer example.

The basic procedure for modeling the human and the elliptical trainer together is almost the same as the first example. However, as mentioned previously, the stabilizing constraints are needed in this example. The stabilizing constraints are used to generate the initial motion of the human body during the inverse dynamics simulation.

Using the implemented system, the model can be simulated successfully (3 sec, 150 time-steps). The result of the simulation is shown in Fig. 25. We conclude that the proposed system can efficiently handle this complex example.

6. DISCUSSION

The competitive nature of the global economy is placing strong pressure for companies to design products that are increasingly easy for humans to use. Thus, current CAD systems should be modified to provide the function by which this 'user-friendliness' can be evaluated at any time in the design process and the evaluation result can be implemented directly into the design process.

Although Finite Element Analysis tools were introduced a long time ago, these tools have only recently been integrated into CAD systems, enabling analysis and design to be carried out simultaneously. We are experiencing a similar phenomenon in the case of human motion and muscle force simulation tools. These tools must eventually be integrated into the CAD system and the product design should be performed with consideration to the effect of the product on the human user. There are several problems to be solved to realize this design paradigm.

First, an integrated framework to accommodate product CAD models and digital human models is required. This system needs to be devised in such a way to prevent losing all the features of CAD systems and simulation programs for human motion and muscle forces.

Second, digital human models of various resolutions have to be developed. It will be necessary to use the right resolution model depending upon the application.

Third, the simulation programs for human motion and muscle forces should become fast enough for the interactive design task. FEA tools were integrated into VAD systems after very fast FEA tools became available.

Fourth, good algorithms should be developed so that the human model can be positioned properly to maximize comfort and ease of use for a given product. We hope the proposed approach in this paper will make a contribution toward this goal.

7. ACKNOWLEDGEMENTS

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