Technologies for the design and retail service of well-fitting eyeglass frames

— Toward the mass customization business —

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The ultimate goal of this research is to realize a mass customization business that enables any consumer to easily obtain a well-fitting product. As the first step towards this goal, an IT-based product recommendation system for eyeglass frames was developed. Using this system, a customer's 3-D face shape is measured, frames of the proper size are recommended, and the impression of the customer wearing an eyeglass frame is simulated for style recommendation. Technologies such as face measurement, size recommendation and impression simulation are integrated based on a 3-D face shape database. When the system is used in a retail shop, the contents of the 3-D face shape database can be expanded, and statistical information on face shape and/or impressions of the face and eyeglass frame can be utilized for product design and retailing services.

Keywords **:** Human sensing, Kansei engineering, Service engineering

1 Introduction

The design concept of "One Fits All" is one solution for universal design. With this idea, one size of product is supposed to comfortably fit all users. This concept is appropriate for designing public facilities and buildings. The "One Fits All" concept is also attractive to manufacturers, as they can reduce manufacturing costs by mass producing just one size. However, it is clear that "One Fits All" is not universally applicable. For instance, one size of shoe cannot fit everyone. For personal products, users are interested in whether they fit their own bodies, not others. While consumers usually use public products designed based on the "One Fits All" concept, they tend to prefer customized products designed for themselves.

Customization based on the skill, know-how and experience of craftsmen has a long history. This type of customization strongly relies on the skill and experience of craftsmen, and it is difficult to apply this approach to mass customization. The aim of this study is to identify human factors that are related to product fitting, to quantify the variations in such factors, and to propose a method to realize mass customization based on engineering. The ultimate goal of this study is to realize a new solution for universal design that can provide customized products "Only For Your Body" for "Anybody", at reasonable prices.

2 Research scenario

Four different solutions have been proposed for providing products of appropriate size. The first solution is "Population Grouping", in which the product provider classifies consumers into several groups, and provides different products for each group to improve the fit. The second solution is "Adjustable Products", in which the product size is adjustable. The third solution is "Finding Well-fitting Products", in which the retailing system can select well-fitting products for specific customers from several candidates (produced based on the first or second solutions) according to customer parameters. The fourth solution is "Mass Customization", in which the whole product or important parts of a product are designed and manufactured based on customer parameters. Although this may seem similar to traditional tailor-made production, "Mass Customization" is based on engineering rather than on the know-how or experience of a specific craftsman. Figure 1 shows the features of the four solutions. Conventional mass production and traditional tailor-made production are located at both ends. The squares indicate cost, the triangles indicate delivery time, and the filled circles indicate customer satisfaction. As Fig. 1 shows the conceptual characteristics of the four solutions, the vertical scale is not meaningful.

"Population Grouping" is the most popular solution. It requires somewhat higher costs than one-size products, but delivery time is shorter because all size variations of product can be stocked. "Adjustable Products" is a typical solution for products such as car driver's seats and office chairs. Additional costs are required for manufacturing adjustable products. In these two solutions, consumers have to select or to adjust the product by themselves. If they do not have sufficient knowledge or experience for selection, the performance of the product can be poor because of a loose or tight fit. The result of our study on shoe fitting [1] is a good example. In this experiment, volunteer subjects selected

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the best fitting shoes from candidate shoes of a wide range of lengths and widths. Subjects with narrower feet selected wider shoes and, subjects with wider feet selected narrower shoes. In the actual market, only shoes of normal width are available. These results suggest that subjects understand the fitting of shoes of normal width as ideal, irrespective of their own foot width. According to various tests, tight fitting shoes block blood flow, while loosely fitted shoes allow larger in-shoe foot movements and larger impact against foot.

The third solution, "Finding Well-fitting Products" includes a service system to recommend suitable products for specific users based on his/her own parameters. Additional costs are required for this recommendation system. If the number of alternatives is too large, the complete range cannot be stocked in the shop, thus resulting in longer delivery times. "Mass Customization", the fifth solution, has been realized as an insole customization service for running shoes. Using a foot scanner, the customer's foot shape is measured at a retail shop, and insoles are immediately manufactured for the customer at the shop. Such processes require additional costs because customization takes time, and special equipment is necessary for manufacturing.

The "Mass Customization" solution is thought to have the greatest potential to satisfy users. However, there are two obstacles. The first is investment by the provider. It is necessary to re-design products for customization, and equipment is required for measuring the user and manufacturing custom parts. Because the investment for mass customization is quite large, it is a difficult decision for the provider. The other obstacle is investment by the customer. There are customers who are willing to pay the additional cost for customized products based on traditional tailor-made customization. However, the market for mass customization is not apparent. Mass customized products are more expensive than mass produced products, and are cheaper than traditional tailor-made products. Customers who prefer traditional tailor-made products may not purchase cheaper mass customized products, while the majority of customers may not pay the additional costs for mass customized products. It may be an effective strategy for creating an apparent market of mass customization to allow the user to experience well-fitting products with a smaller investment. Therefore, we took the "Finding Well-fitting Products" solution as a tentative step towards "Mass Customization" in order to allow the user to experience a good fit at a reasonable price. An IT-based "Finding Well-fitting Products" system can store user body data and purchasing behavior as the system operation log, and the stored information can be utilized in product sizing for "Mass Customization". Good experiences may induce additional investment by users. Subsequently, providers are encouraged to invest in equipment.

The aim of this study is to integrate technologies for the "Finding Well-fitting Products" solution based on the concrete application of research into eyeglass frame retailing. The domestic market size for optical goods is 100 billion yen per year (2002). There are around 15,000 eyeglass shops in Japan. Figure 2 shows the final goal image of the system that would be operated in these retail shops. Customer's facial photos are taken at a retail shop, and a 3-D shape of the customer's face is generated from multiple photos. Based on the measured data, the system recommends a suitable size of eyeglass frame from prepared candidates. Elemental technologies for size recommendation include measurement technology that is simple and inexpensive enough to be used in retail shops, designing technology considering human face shape variations, and size recommendation technology. The system also recommends styles of eyeglass frame that makes the customer look intelligent, gentle, etc. This system shows the simulated impression ratings by a third party for the combination between the face of the customer and the selected eyeglass frames. These style recommendation services could be provided by shop clerks through traditional tailor-made customization based on their know-how and implicit knowledge obtained through experience. In this

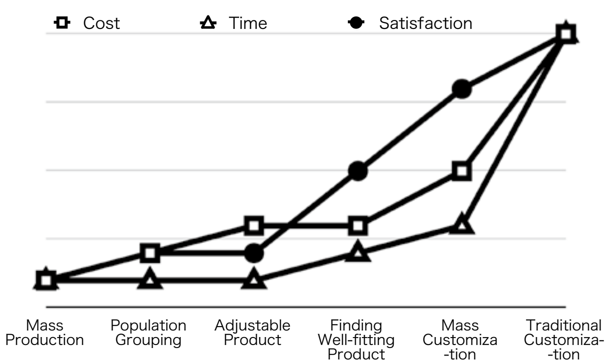

Fig. 1 Cost, delivery time, and satisfaction of customers with various manufacturing methods.

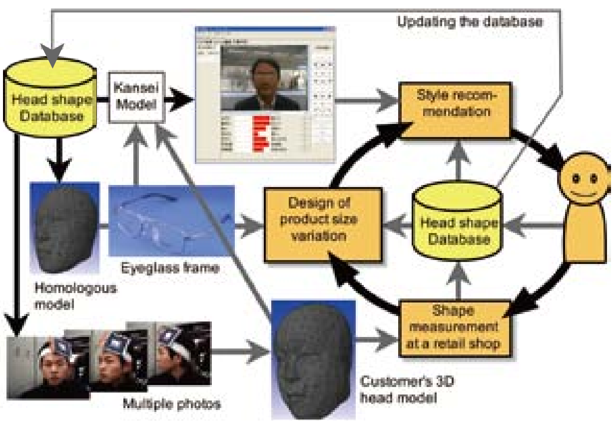

Fig. 2 A system to produce eyeglass frames according to the "Finding Well-fitting products" approach.

study, we developed a computerized recommendation system based on explicit knowledge. Three elemental technologies (easy measurements, size recommendation and style recommendation) were developed based on a database of 3-D face and head shapes. These technologies may be applied to the business through a scenario, as shown in the right side of Figure 2. With this scenario, the database can be expanded continuously through the business cycle. In the present paper, we describe the database of 3-D face and head shapes and the three elemental technologies. Subsequently, integration of these technologies and validity for actual retail services are discussed.

3 Elemental technologies

3.1 Homologous human body shape modeling and database of 3-D face and head shapes

The database of 3-D face and head shapes was the technological foundation of the three elemental technologies. In this section, general methods for human body measurement and homologous shape modeling are described. Subsequently, concrete technologies for applications such as head scanning technologies and head modeling methods are described.

Optical scanning technologies are used commonly for human body shape measurement. A patterned light source is projected onto the body surface, and the reflected light is captured by camera from a direction different from the light source. The 3-D coordinates of the surface are calculated by triangulation [2]. The human body shape obtained by scanning consists of 3-D coordinates of a large number of data points (many millions) and 3-D coordinates of dozens of anatomical landmarks. Anatomical landmarks are feature points based on anatomical correspondence. Many landmarks are defined based on specific positions on bones. An expert anthropometrist palpates and determines the landmark locations, and places markers on the skin surface before scanning. Most body scanners can automatically detect the markers on landmarks and calculate their 3-D coordinates. Landmark locations have the same anatomical meaning in all subjects, and all subjects have the same number of landmarks. However, the number of landmarks is too small to represent the 3-D body shape.

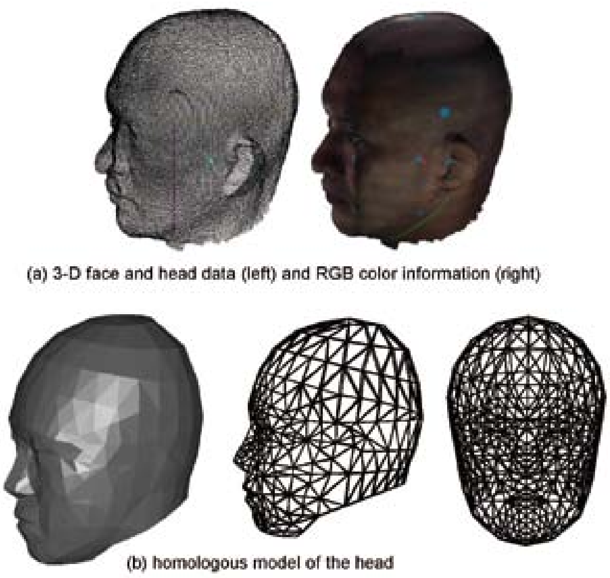

Fig. 3 Examples of 3-D face and head data (a) and homologous model of the head (b)

The number of data points on the body surface is large enough to represent the 3-D body shape, but the number differs between subjects. It is difficult to compare 3-D body shape in different subjects, as the number of landmarks is too small to describe body shape, and the number of data points on the body surface differs between subjects. Therefore, we proposed homologous body shape modeling. With homologous body shape modeling, the body surface shape of any subject is described with the same number of data points and the same topology. We proposed polygonal representation. Body shape is described with k piece of 3-D coordinate vector $\overline{T}$, which has $k \times 3$ components. The average body shape of m persons can be calculated easily from multiple shape vectors $T_1, T_2, ...$, and T_m. By analyzing the matrix $M=[T_1, T_2, ..., T_m]$ using the principal component analysis (PCA), eigenvector P is obtained.

Body shapes for m persons can be represented in the eigenspace by using principal components A_1 - A_m. When n principal components explain sufficient variance, human body variations can be described in the eigenspace of n dimensions (n<number of data points). Reducing the number of items to represent human body variations is effective for product sizing. Moreover, virtual homologous body models can be generated from eigenvector and principal component scores. A virtual homologous body model is calculated by the following equation:

$$T = \overline{T} + P(n) \text{ x } A(n) \text{ ... } (1)$$

where, $P(n)$ indicates first n eigenvectors, and $A(n)$ indicates scores for first n principal components.

Commercial systems are available for 3-D face and head shape scanning. For eyeglass frame design, the conventional scanning system had several technical issues; regions behind the ears were occluded, anatomical landmarks were not automatically obtained, and a homologous model was not automatically generated. We developed a new face and head scanning system to solve these issues. Twelve visible ray projectors were located around the head, and patterned light was projected onto the head. The human head with the light pattern was captured by 12 cameras. The projectors and cameras were carefully located in order to reduce the occlusion of regions such as under the chin, under the nose and back of the ear. Using this system, the head shapes of 52 Japanese males (18-35 yr) were measured. The obtained data consists of millions surface data points, RGB color information of the data points, and around 80 anatomical landmarks (Figure 3(a)). A homologous head model without the external ears consisting of 485 vertices and 838 polygons was then generated (Figure 3(b)).

3.2 Size variation design[4]

Conventional eyeglass frames vary in size. The sizing method is very simple; lens width and temple length are changed in proportion. The sizing method does not represent variations in the human face. Thus, we designed a new sizing system that could effectively cover the variations in the human face using a mid-facial homologous shape model consisting of 211 vertices (Figure 4). As mentioned in Section 3.1, PCA can compress information on shape variation. However, PCA is not efficient enough for grouping subjects because it is based on linear transformation. Therefore, we used the multi-dimensional scaling method (MDS). The inter-individual shape distance was defined by the following formula:

$$D_{ij} = | T_i - T_j |$$

where, T_i indicates the vertices vector of i-th subject and T_j indicates that of j-th subject. The inter-individual distance D_{ij} is calculated from the summation of the Euclidean distances between the corresponding vertices. When the number of subject is m, the distance matrix ($m \times m$) of inter-individual shape distances is calculated. By analyzing the distance matrix using MDS, the location of each subject is assigned in a low-dimensional space. The fit of the model is evaluated using RSQ, the squared correlation coefficient between elements of original distance matrix and elements of the distance matrix calculated from the obtained low-dimensional solution.

Fig. 4 Homologous model for the middle face

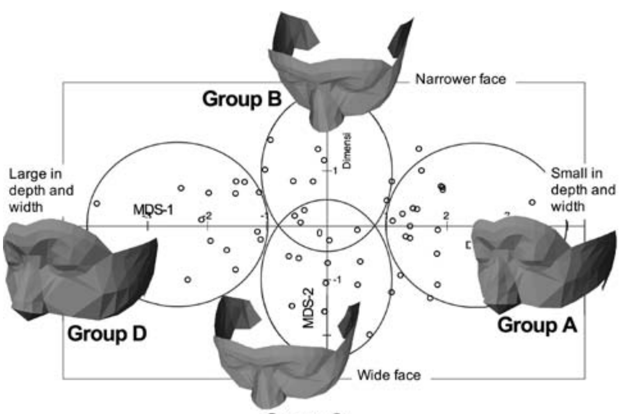

Fig. 5 Distribution of middle face shapes in 52 young adult male Japanese

Analyzing the variation in mid-facial shapes by MDS, the coefficient of determination (RSQ) was 0.95 for the 5-dimensional solution, whereas at least 15 principal components are needed to explain 95 % of the total variance. Figure 5 shows the distribution map of the subjects based on the scores for the 1st and the 2nd scales of the MDS. The obtained MDS scales were interpreted using correlation coefficients between the MDS scores and facial dimensions. The 1st scale was related to the face size, particularly the depth, and the 2nd scale to the face width and the inclination of the face. These two scales account for 83 % of the variation in the Japanese face. The 3rd scale was related to shape of the nose, and the 4th scale to the proportion between the face width and the interpupillary distance. The 3rd and the 4th scales are not strongly related to fitting of the eyeglass frames.

We decided to develop 4 eyeglass frame sizes considering profitability of manufacturing and distribution. Four size groups were defined as shown in Figure 5; namely subjects were divided into 3 groups based on the scores for the 1st scale representing the size, and the mid-size group was divided into two groups based on scores for the 2nd scale. The average face shape to represent the size group was calculated for each group. Well-fitting eyeglass frames were designed and manufactured based on the average face by the collaborating company (Figure 6).

In order to validate the fitting of new eyeglass frames, 38 male subjects were recruited (average age, 24.5 yr). For each subject, the location in the MDS distribution map (Figure 5) was estimated by multiple regression based on 15 facial dimensions, and the size group was determined. New frames for the 4 size groups and a conventional frame of the same style design were used for the validation study. The tightening force and the slip range after the subject shook the head were measured. Sensory evaluation of fitting was also conducted using a 5-point scale rating. New frames of the

Fig. 6 Preproduction sample of eyeglass frame using the new sizing system

proper size got significantly better scores for overall fit than the conventional frames ($p<0.01$). Moreover, the tightening force was significantly smaller in the new frames ($p<0.01$). On the other hand, no significant differences were observed in slip range. Thus, the new frames fit without slip and had a smaller tightening force.

3.3 3-D head shape reconstruction from multiple images[5]

Location in the subject distribution map could be estimated from 15 face dimensions, and a suitable size of eyeglass frame could be selected. An expert anthropometrist is necessary to obtain reliable face dimensions, thus it is difficult to use this method in actual retail shops. In addition, 15 face dimensions are not sufficient for reconstructing 3-D face shape, which is used for computer graphic representation (Figure 2), while the special 3-D face scanner mentioned in Section 3.1 is too large and expensive to use in retail shops. Therefore, a novel measurement method for human body shape was developed.

The variation in human bodies can be represented in the eigenspace with a smaller number of independent dimensions (Section 3.1). Namely, any human body shape can be described using only dozens of principal components rather than millions of data points. Therefore, we developed a new method for reconstructing, rather than measuring, the 3-D head shape of an individual. The average head shape is used as the initial shape, and unknown values (principal component scores describing the individual shape) were obtained by minimizing the differences between camera images and the projected image of the 3-D head shape reconstructed from principal component scores ($A(n)$ in equation (1)) Reconstructed 3-D head shape was projected into image planes based on calibration parameters of multiple cameras. The difference between the real 2-D image and the projected image was evaluated by the edge distance of two images. The principal component scores $A(n)$ were optimized to minimize image differences, and the optimal 3-D shape was obtained from the optimized principal component scores (Figure 7). The calculated 3-D head shape was compared with 3-D shape measured by the head scanner (Section 3.1), and the average error was found to be 2.0 mm.

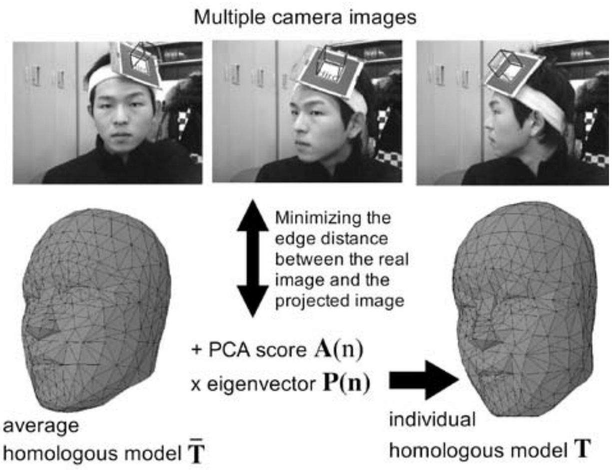

Fig. 7 Reconstruction of 3-D face and head shape from multiple images

This technology is not a measurement technology, but is a reconstruction technology using multiple cameras based on the database of homologous body shapes. However, this technology has a similar function as a measurement technology, because 3-D head shape can be obtained from multiple cameras to an accuracy of 2.0 mm. As this method is not based on triangulation between a camera and projector, patterned light projection and scanning processes are unnecessary. A homologous model of an individual can be obtained by simultaneously capturing images with multiple cameras. Face dimensions are extracted from the model, and used for recommendation of eyeglass frame size. Furthermore, even when part of the head is occluded, the reconstructed model is always complete.

3.4 Computational estimation of the impression for the face and frame[6,7]

Size recommendation can be realized by size variation design technology (Section 3.2) and individual head shape measurement technology (Section 3.3). In this section, style recommendation technology is described. This technology is for estimating the impression ratings of the combination of an individual face and a selected eyeglass frame.

Words were used to describe the impression of the face and the eyeglass frame. In a preliminary experiment, we selected 42 adjectives from about 100 words obtained from a dictionary. Photographs of 10 different faces with different eyeglasses were presented to young adult female subjects and impression of each photograph was rated against the 42 adjectives. The ratings were analyzed using a factor analysis, and 4 factors were extracted. The 4 factors were interpreted as “gentle - stern”, “cool - hot”, “cheerful - quiet” and “younger looking - older looking”. The following 3 pairs of adjectives were added based on the original marketing research of the collaborating eyeglass frame maker: “sophisticated - unstylish”, “natural - unnatural” and “optimistic - nervous”. Impression ratings for these 7 pairs of words were obtained for images of a face and frame by experiments using sensory evaluation. We hypothesized that impression rating could be estimated as a function of shape factors for the face and eyeglass frame. Therefore, we identified this function based on experimental data, and validated the performance of this function using actual data.

Generated virtual face images were used for the experiment. Virtual face images were generated to cover the variations in young adult male Japanese faces using the database of

3-D face and head shapes. Head data was analyzed by MDS, and virtual 3-D homologous face models with scores of +3 standard deviation (s.d.) or –3 s.d. for only one of the 4 scales, such as (+3 s.d., 0, 0, 0), (–3 s.d.,0, 0, 0), (0, +3 s. d., 0, 0), etc., were generated. Virtual shapes at the center of distribution (average shape) or located between 2 scales were also generated. In total, 18 representative face models were generated.

The homologous model described in Section 3.1 did not contain color information, such as eyebrows and lips that influence impression; therefore, a 2-D frontal face model including such information (Figure 8) was generated for each of the virtual shapes. The 3-D model of an individual was deformed into each of 18 generated models using the Free Form Deformation technique. Using each of the obtained transformation grids, the scan data of the individual with color information was deformed. The obtained representative 3-D face shape with color information was then projected onto the frontal plane. From the projected 2-D face with color information, a 2-D frontal face model including eyebrows and lips was created. The average texture of the young adult male Japanese was mapped onto the 2-D face model [8]. Through this process, 18 representative face images with color information were generated. Twelve eyeglass frames of different materials, types and shapes were selected. In order to reduce the time needed for each experiment to 30 minutes, 12 sets of 18 images were selected from 216 images (18 faces × 12 frames). Every set contained different faces and different frames.

Participants were 300 young adult females. They evaluated one set of images (18 images) randomly selected by the web questionnaire system. The impression rating was evaluated by the visual analog scale method (VAS). Participants evaluated the image by moving the pointer on the scale between each pair of words in the web system (Figure 9). A computational model to estimate the impression rating from shape factors of the face and the frame was obtained by multiple regression (stepwise procedure). The dependent variable was the impression rating for each pair of words, and explanatory variables were the face dimensions and proportions, eyeglass frame dimensions and proportions, principal components of lens shape descriptors. Multiple correlation coefficients ranged from 0.784 to 0.901 for all impression ratings. Dimensions and proportions of the faces and eyeglass frames, and principal components of lens shape were contained in the explanatory variables for all impression ratings (Table 1).

For the validation study, the following 12 face images were used: (1) virtual face images that were not used in the main experiment to develop the model, (2) a virtual face image that was close to the average face, (3) deformed actual face images, and (4) images that were used in the main experiment. Twelve images of faces with eyeglass frames were presented to another 59 young adult female participants, and impression ratings of 7 pairs of adjectives for 12 images were obtained. Comparing the impression ratings for validation images of (4) with those for the same images in the main experiment, it was found that the participants of

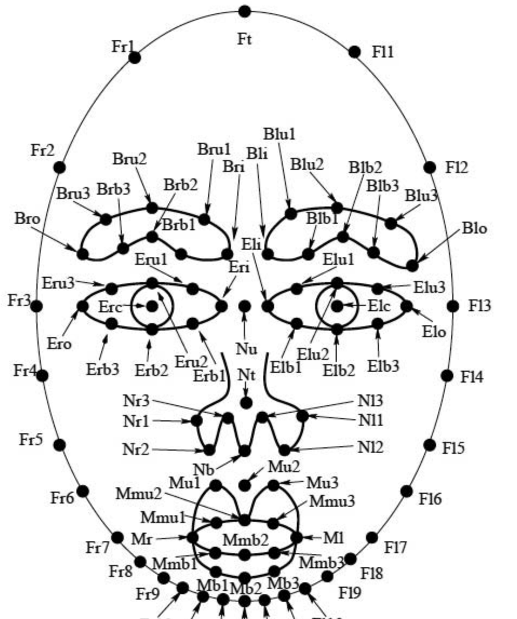

Fig. 8 2-D front face model used. From Mukaida et al., 2002

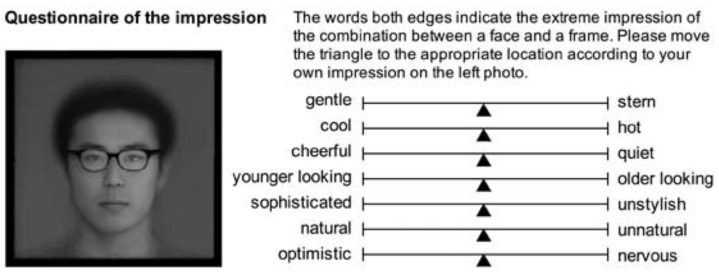

Fig. 9 Example of Web-based questionnaire for impression rating

Table 1. Number of variables adopted in estimation functions (stepwise multiple regression)

Word pair describing impression	R	Face measurement	Eyeglass frame measurement	PCs for lens shape
Gentle－Stern	0.892	11	3	1
Cool－Hot	0.901	8	5	2
Cheerful－Quiet	0.821	8	1	1
Younger looking－Older looking	0.784	8	3	2
Sophisticated－Unstylish	0.834	5	6	2
Natural－Unnatural	0.871	5	3	1
Optimistic－Nervous	0.863	9	1	1

the validation study were equivalent to those of the main experiment. The residual error between estimated ratings and actual ratings for validation images were calculated for images of (1) and (2). The error was within 10 % for all impression ratings. Moreover, a similar error range was observed in the deformed actual face images of (3). It was confirmed that the computational model could be utilized for real face images. The hypothesis of this study, that impression rating can be estimated by a function of shape factors of the face and eyeglass frame, was thus validated.

3.5 Style recommendation system

A style recommendation system based on the computational model to estimate impression ratings (Section 3.4) was developed. This is part of the recommendation system in Figure 2, but focuses on style recommendation using 2-D face images. Customer images are captured by a USB camera connected to a PC, and a 2-D homologous face model (Figure 8) is generated automatically. In the present system, the interpupillary distance is measured directly and the value is used for scaling. Scaling problems can also be solved by camera calibration in the future. Images of 12 eyeglass frames used in the experiment and their shape factors are registered in the system. Obtaining a 2-D model of the customer, the impression ratings of all pairs of adjectives for 12 eyeglass frames are calculated immediately. The ratings are presented on the system as a relative scale for the 12 frames with a composite image of the face and selected frame (Figure 10).

4 Integration of elemental technologies

The aim of this study is to realize a solution for “Finding Well-fitting Products” through an application study aiming to fit eyeglass frames to individual customers. Elemental technologies were developed for this purpose and they were integrated to realize the solution presented in Figure 2. Three elemental technologies described in Section 3, size variation design, head shape reconstruction, and estimation of impression ratings, were integrated into an off-line system. Part of this system was completed as a demonstration.

Fig. 10 Style recommendation system for eyeglass frames based on Kansei (sensibility) modeling.

The most important foundation in this study is the database of 3-D face and head shapes. Homologous modeling and the database are essential for integration. All elemental technologies developed in this study require the database. For instance, the head shape reconstruction method requires the database obtained using another measurement method. The reconstruction method itself is not complete without the database of homologous models of head shape. This promotes the advantage for system providers who have a database. The system provider can keep the advantage of the database by applying the system. When the provider applies the system at a retail shop, the database can continuously be expanded by adding customer data to the database. The compiled data can be used for both proper size grouping of products, as well as for robust shape reconstruction using a multi-camera system.

5 Discussion

In this section, the industrial and social validity of this study are discussed. Based on the size variation method described in Section 3.2, new eyeglass frames with proper sizing were developed by the collaborating company and were sold on the market. Subsequently, the company used the sizing method for other eyeglass frames. It was thus confirmed that the method is valid for industry.

The 3-D shape reconstruction method described in Section 3.3 has a similar function as 3-D shape scanning technologies, but with this method, complete 3-D shapes can be obtained very quickly and without laser scanning. The error of 2 mm is larger than the 0.5 mm of conventional scanning technologies [3], but is small enough for size and style recommendation. The system contains multiple digital cameras, and registration and time control for projectors and cameras are not required. The features of the system, such as its low cost, size, lack of laser projection, and quick and complete measurement, are superior to conventional systems for retail use. The style recommendation system described in Sections 3.4 and 3.5 is only used for demonstration purposes. This system has been received well by visitors, with comments such as “it is fun to select eyeglass frames with this system”.

Throughout this study, the obstacles to investment from providers were reduced by the development of efficient size variation designs using existing manufacturing resources, and a low-cost head shape measurement system. When this recommendation system is operated in retail shops, providers can store the information on face shape and product selection from the log of the recommended system. Such information can form the foundation for “Mass Customization”. From the customers’ point of view, recommendation technologies for both size and style induce investment in more expensive products. Such interaction between providers and customers creates a new solution for universal design, “Only For Your body” for “Anybody”.

Storing body data through retail businesses using the developed system may lead to the formation of intellectual infra-structure. Databases of human body shape have been collected and stored by institutes that have special equipment and skills based on government funding. The data has been obtained cross-sectionally in specific locations over short periods of time. The Research Institute of Human Engineering for Quality Life (HQL) measured 34,000 Japanese during 1992-1994, and they measured other 8,000 Japanese during 2004-2006. In North America, 4,000 people were measured in CAESAR project in the last decade. In contrast, longitudinal human body data can be stored at distributed retail shops by the developed system. History of body shapes for an individual can be stored in many locations around the world. Large amounts of human body data can be stored on a daily basis. This would allow social intellectual infra-structure. It is also expected that the funding resources to create this infra-structure would shift from governmental to nongovernmental sources. Stored human body data without personal information could then be used for size variation design (Section 3.2) and measurement technology (Section 3.3). Relationships between body shape and buying history could also be utilized for creating new Kansei models. In the future, a practical system for retail shops may be developed with the collaborating company, and the system could be applied to an actual retail shop.

References

[1] M. Kouchi, M. Mochimaru, H. Nogawa and S. Ujihashi: Morphological fit of running shoes, *Perception and Physical Measurements, the 7th Symposium on Footwear Biomechanics*, 38-39 (2005).

[2] M. Mochimaru and M. Kouchi: *Jintai o hakaru-sunpo · keijo · undo* (Measurement of Man: Size, Shape and Motion), Tokyo Denki University Press (2006) (in Japanese).

[3] M. Mochimaru, M. Kouchi, and T. Oya: Jintai keijo no kosoku · kakure nashi keisoku sochi no kaihatsu (Rapid and complete body shape scanners), *Proceedings of the 19th Sensing Forum*, 47-52 (2002) (in Japanese with English summary).

[4] M. Kouchi and M. Mochimaru: Analysis of 3D face forms for proper sizing and CAD of spectacle frames, *Ergonomics*, 14-47, 1499-1516 (2004).

[5] Y. Ito, H. Saito, and M. Mochimaru:Tangan kamera gazo retsu karano kaibogaku teki kao keijo deta besu o mochiita kao keijo fukugen (Face shape reconstruction from image sequence taken with monocular camera using shape database), *14th International Conference on Image Analysis and Processing* (ICIAP2007),165-170 (2007)(in Japanese).

[6] M. Mochimaru and M. Kouchi: A KANSEI model to estimate the impression ratings of spectacle frames on various faces, *SAE Digital Human Modeling for Design and Engineering Symposium* 2005, 2005-01-2693 (2005).

[7] K. Tanaka, M. Kouchi, and M. Mochimaru: Megane furemu no sutairu tekigosei no kansei moderu (A KANSEI model to estimate the impression ratings of spectacle frames on various faces), *Proceedings of the 8th Conference of Japan Society of Kansei Engineering* (2006) (in Japanese).

[8] S. Mukaida, M. Kamachi, M. Oda, T. Kato, S. Yoshikawa, S. Akamatsu, and K. Chihara: Sosasei o koryo shita kao gazo gosei shisutemu:FUTON - kao ninchi kenkyu no tsuru toshiteno hyoka - (Facial image synthesis system: FUTON - evaluation as tools for cognitive research on face processing -), *The Transactions of the Institute of Electronics, Information and Communication Engineers*, J85-A-10, 1126-1137 (2002) (in Japanese).

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Masaaki Mochimaru is the Deputy Director of the Digital Human Research Center at the National Institute of Advanced Industrial Science and Technology of Japan. He received his Doctoral degree in Engineering from Keio University. His research interests are: human body shape measurement technologies, deformation and motion; footwear biomechanics (shoe design based on foot factors); digital human modeling for product assessment; and the application of ergonomics to product design (clothes, eyeglasses, gloves, computer mouse etc). Dr. Mochimaru has received many awards for his work. He is a member the IEEE Computer Society, SAE International, the International Ergonomics Association, the Japan Ergonomic Society, the Society of Biomechanisms Japan, The Society of Instruments and Control Engineers.

Makiko Kouchi
Makiko Kouchi is a Prime Senior Researcher in the Digital Human Research Center at the National Institute of Advanced Industrial Science and Technology of Japan. She studied physical anthropology and received her Doctoral degree in Science from the University Tokyo. Her research interests include variations in human body due to aging, secular change and movement, as well as modeling and analysis of 3D human body shape. Dr. Kouchi has received such awards as the Promotion prize from the Anthropological Science for a Significant Paper (1992), the AIST Director-General’s Award (2000), and a Basic Research Award from the International Society of Biomechanics, 5th Footwear Symposium (2001). She is a member of the Anthropological Society of Nippon, the Japan Ergonomic Society, and the Japan Society of Biomechanisms.

Discussion with reviewers

1. Methods for improving fit

Question (Motoyuki Akamatsu)

Authors listed 1) Population Grouping, 2) Adjustable Products, 3) Finding Well-fitting Product, 4) Mass customization, and 5) Traditional customization as methods for improving the fit. I believe that Method 3) is for improving the fit obtained by Method 1), rather than a method located between Methods 2) and 4). Therefore, I believe that Method 3) should be considered as a secondary method to make up for the shortcomings of Methods 1) and 2). Because both methods depend on the subjective judgment of the user, true conformity cannot be attained. In addition, Method 3) is the basis of Method 4).

Answer (Masaaki Mochimaru)

Thank you for your comments. As you stated, 3) Finding Well-fitting Product does support the shortcomings of 1) Population Grouping and 2) Adjustable Products. Therefore, we revised the text as follows: After describing 1) Population Grouping and 2) Adjustable Products, we state that good fit cannot be obtained if the selection depends on user preference, citing our previous study as an example. We then state that Method 3) Finding Well-fitting Products overcomes these issues.

Your last comment indicates that the relationship between the characteristics of users and characteristics of products will be accumulated by providing services for “Finding Well-fitting Products”, and such information will be the basis for “Mass Customization”. We agree with this opinion. As our original manuscript did not mention this point, we now discuss it in the Discussion.

2. Grouping subjects and the validity of evaluation

Question (Motoyuki Akamatsu)

Please explain the grouping of subjects into 4 groups. Did you evaluate the validity of each evaluation study with regard to which group the 38 subjects belonged and the differences between each subject and average shape in the 4 groups?

Answer (Masaaki Mochimaru)

(1) Grouping subjects

As the shape variation followed the normal distribution, there was no scientific way to divide subjects into a limited number of groups. Theoretically, the more groups, the better the fit. Therefore, in this study, the collaborating company examined the maximum possible number of groups from the viewpoint of profitability in manufacturing and distribution, and decided on 4 groups. We then had to determine how to cover the variation within the limit of 4 groups. In this study, we divided the scores for the 1st scale, which explained the largest variance, into 3, and the group with near average scores for the 1st scale was divided into 2. As shown in Figure 5, Groups A and D cover larger areas than Groups B and C. This is because by setting different ranges of scores for the 1st and the 2nd scales between the 4 groups, we attempted to minimize the difference in shipments between the 4 groups. In other words, numbers of people who would be assigned to the 4 groups are about the same in number. Such reasoning is described in reference [4], and we have added an overview to the manuscript.

(2) Evaluation study

We recruited subjects so that the numbers of subjects assigned for the 4 groups did not differ substantially. Because 3D shape was not measured for the 38 subjects, the shape difference between each subject and the average for each group is unknown. However, the difference was within 3 mm for head dimensions. This is described in the reference cited, but we now mention it in the text.

3. Head dimensions measured

Question (Motoyuki Akamatsu)

Section 3.3 describes “using 15 face dimensions”. How did you decide the 15 face dimensions?

Answer (Masaaki Mochimaru)

Details are described in the reference cited. We measured about 50 items for all subjects. The 15 measurements were adopted for regression equations to estimate the scores for the 1st and the 2nd scales, using stepwise regression analysis. We intentionally selected measurement items that can be measured easily and reliably, and performed the stepwise regression analysis several times. We did not describe the details in the text.

Our initial plan was to use these 15 measurements rather than 3-D shape for selecting eyeglass frames (see references), but this was not accepted by the collaborating company, as retail staff do not possess the necessary skills in anthropometry. Therefore, we decided to develop a low-cost head measurement system.

4. Future works

Question (Motoyuki Akamatsu)

Please include a discussion of the future direction of the project, areas that need to be improved, and technical breakthroughs yet to be realized.

Answer (Masaaki Mochimaru)

Of course, there are some areas that require further work. For example, the effects of hairstyle on style recommendation have not been investigated. It is clear that there is an effect based on the results of preliminary experiments, but we currently lack the computer graphics technology to naturally change hairstyles. Future works include designing parts (nose pad and bow) and finite element analysis for estimating the pressure distribution between these parts and the face, as well as the sensation of touch. Another incomplete aspect is the technology for utilizing the information on product selection and satisfaction. Without this technology, simultaneous data accumulation, updating size variation designs and Kansei evaluation are impossible; this system is merely a tool for sales support. This will be studied further after systems such as that presented in this paper are practically used in shops.

5. Other applications of this technology

Question (Motoyuki Akamatsu)

Similar systems may be used for other products, such as clothes and shoes. Will the technologies for other products be the same as with this system, or is there something specific to eyeglass frames?

Answer (Masaaki Mochimaru)

We believe that this approach for measuring the human body and selecting the best fitting products from size variations has general applications. Such methods are already used for running shoes in shops. However, applications for selecting clothes are not very popular, as few consumers would be willing to undress for a 3-D scan. We believe that improved technology for 3-D measurement for clothes, or other businesses related to body scanning may solve this problem.

For recommendations based on Kansei modeling, style design and fit are more independent elements for eyeglass frames and running shoes, while they are closely related with shoes and clothes. Therefore, the present system that recommends size and style independently may not be applicable to shoes or clothes. However, recommendation systems for those products are possible and should be studied in the future.