An Analysis of Natural Motion for Product Design: Refrigerator Half-Guard Installation Part Design

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Ergonomic product design which considers users' natural-use motion is of importance to improve the usability and satisfaction of a product. A five-step process of product design was developed in the present study by measuring and analyzing users' natural product-use motion with a motion capture system. The developed process was applied to the ergonomic design improvement of a half-guard installation component of a refrigerator; new guard designs (diagonal and arc shape) were developed with the process and evaluated in terms of validity during the development as two measures (task satisfaction and similarity of natural motion). According to the evaluation result, the satisfaction at putting in- and out-task of new guard designs (diagonal and arc shape; 6.3 ± 0.5 points) was significantly higher than that of existing guard designs (3.3 ± 1.0 points); the difference between natural motion and product-use motion in new guard designs (1.0 ± 0.3 cm) was significantly less than that of existing guard designs (nipper and rectangular shape; 2.0 ± 0.2 cm). The proposed process of natural motion analysis and product design is widely applicable to ergonomic product design and evaluation.

INTRODUCTION

Users' posture and motion of a product have been considered as important measures for ergonomic product design and evaluation. For example, Nelson et al. (2000) analyzed finger joint motions for various design types (e.g., pitch, roll, and yaw angles) of a computer keyboard; Rempel et al. (2007) analyzed users' wrist joint motion to design an ergonomic keyboard. Furthermore, Karlqvist et al. (1999) evaluated body joint movement and usability for preventing musculoskeletal disorders (e.g., carpal tunnel syndrome and neck-shoulder myofascial pain syndrome) relevant to computer use; Moffet et al. (2002) analyzed posture and motion variations of users' neck, elbow, and wrist when a laptop was used on a desk and on the knees.

Several studies have been conducted to design products by considering natural posture and motion that users prefer. Allie et al. (1999), who defined the concept of natural motion as physical natural movement to reduce muscle fatigues, proposed the design of a comfortable seatback by considering the natural movement of the spine in seating posture. Chang (2006) identified range of motion (ROM) of eight body parts (e.g., wrist, elbow) in natural cleaning motions to design an ergonomic vacuum cleaner and applied the identified ROM to usability evaluation. Additionally, by considering users' natural posture and motion, Nyberg and Kempic (2006) proposed a diagonal door for washing machine to facilitate comfortable posture during loading and unloading.

Although several studies considering users' motion have been conducted to design ergonomic products, the design processes of the previous studies are mostly based on qualitative, not quantitative, information. As an example, Allie et al. (1999) proposed design of a comfortable seatback was insufficient in presentation of basis for the specific design method and usability evaluation of developed seatback design. Therefore, development of a new design process in which the users' natural motions are more systematically and quantitatively reflected in product design and ergonomic evaluation of newly developed products are necessary.

This study developed a product design process considering users' natural motion of product-use and analyzed its validity to product design. Natural motion was recorded at a time that users felt comfortable and was as natural as much as possible while they used the given products. Recorded natural motion was applied as fundamental information of product design improvement through regression analysis. Moreover, improvement effect of the newly designed product was evaluated ergonomically at the aspect of (a) use motion convenience and (b) task satisfaction. The proposed product design process and usability evaluation method were applied to the design of installation parts (groove and projection) of refrigerator guards (Figure 1).

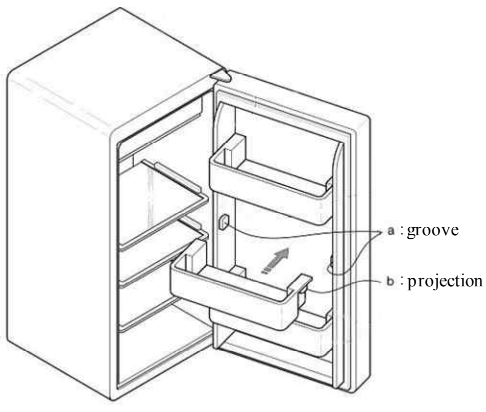


Figure 1. Installation parts (groove and projection) of refrigerator half-guard

NATURAL MOTION ANALYSIS AND DESIGN DEVELOPMENT

The proposed product design method consists of a five-step procedure (Figure 2) of natural motion analysis. First, the use process and motion of a product are understood by task analysis. Second, preferred natural-use motion is recorded during use of a product. Third, the design dimensions are proposed by analyzing the recorded natural motions for application to product design. Fourth, design alternative are developed based on the identified natural motion. Lastly, the design alternatives are evaluated.

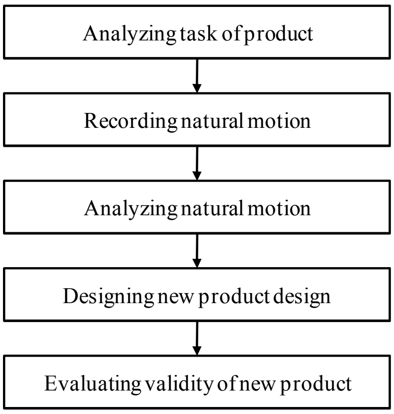


Figure 2. Product design procedure based on natural motion

Analyzing task of product

Task analysis is the step of analyzing task characteristics (e.g., relevant body parts, pattern of product-use motion) of a product. For example, from the focus group interview (FGI) results of 20 homemakers, the assembly and disassembly of guard installation were surveyed. The guard installation task is conducted by using installation parts (groove and projection; Figure 3).

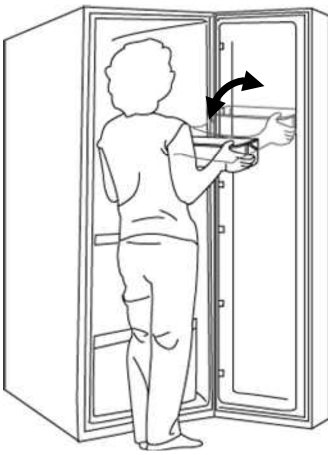


Figure 3. Product-use task analysis
(Refrigerator half-guard installation task)

Recording natural motion

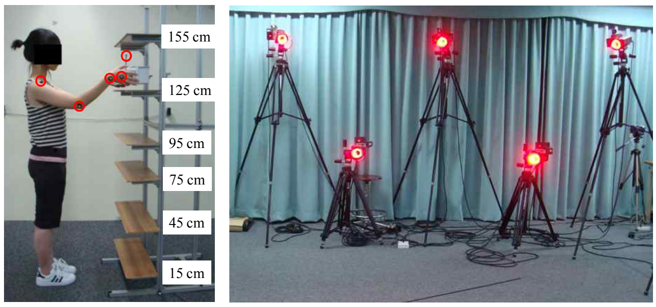
In this step, users' natural motions were recorded. *Natural motion* is defined as the motion that "the user comfortably and naturally uses to operate the product without any physical inconvenience"; it can be an essential design parameter. In this step, a measurement protocol (e.g., participants, apparatus, recording procedure) of natural motion was developed and applied to recording natural-use motion of the half-guard.

Participants

Eighteen homemakers (average age: 44; SD = 9) were chosen for measurement of natural motion because they use the refrigerator more than non-homemakers. To recruit participants diverse in stature, participants were selected by dividing the stature of the Korean female population (age: 30 ~ 50; Size Korea, 2010) into three categories by percentile (< 33^{th}, 33^{th} ~ 67^{th}, 67^{th} <). The average stature of the participants was 157.4 cm (SD = 5.3; range = 148.7 ~ 173.5 cm).

Apparatus

The present study fabricated prototypes of guard installation parts and a motion capture system was used to record natural-use motion for guard assembly/disassembly (Figure 4). Prototypes were developed by considering not only existing refrigerator characteristics but also eliminating any obstacles (e.g., groove and projection) which can affect natural-use motion. For example, guards' installation heights were selected from six different heights (15, 45, 75, 95, 125, 155 cm) by considering the characteristics of existing refrigerators. Hawk-I (Motion Analysis Co., U.S.A.; Figure 4.b) was used to record arm and shoulder movement (sampling rate = 60 Hz). Four reflective markers (Φ = 1.2 cm) were attached onto the right arm (shoulder, elbow, wrist, wrist-dorsal), and one marker on the guard (Figure 4.a).



(a) Experiment prototype (b) Hawk-I motion capture system

Figure 4. Experimental set-up for natural motion recording

Experiment procedure

The natural-use motions of half-guard installation were recorded in 6 steps: (1) the purpose of the experiment and experimental process were introduced and a written informed consent was obtained; (2) selected anthropometric data of the participant were measured; (3) reflective markers were attached to the designated locations; (4) the guard installation task was exercised using the prototype; (5) natural-use motion for the guard installation task were recorded at six different heights; and (6) debriefing was conducted.

Analyzing natural motion

The recorded natural motions were quantitatively analyzed to develop the parameter of new product design. For example, the recorded motions were quantitatively analyzed by regression analysis (Figure 5; Table 1). The regression functions of natural motions represent the participants' representative motion trajectories.

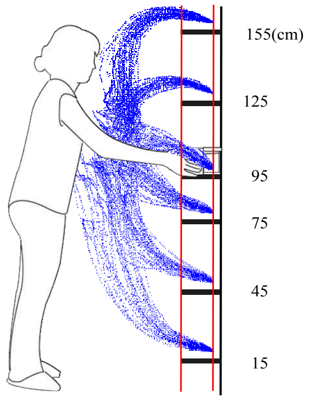


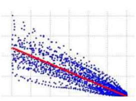
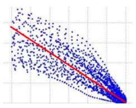
Figure 5. Recorded natural-use motion for guard installation

Designing new product design

The design process of the new product based on the representative motion trajectory consisted of three steps. First, the design variables which can affect users' motion were identified and the design characteristics were analyzed through the benchmarking results from existing designs. Second, the new design alternatives were developed by analyzing natural motion trajectory. Lastly, design parameters of the new design alternatives were defined and a mock-up was made for its validity evaluation.

The present study selected *installation part shape* as a design variable of the guard. And from the information of natural motion trajectory characteristics (e.g., gradient and curvature), diagonal and arc shapes of guard design were newly designed by linear and non-linear regression equations (Figure 6). Moreover, to improve the visibility of the guard installation task, assembly reference points (ARPs) were added on the door side of the refrigerator. Lastly, prototypes of the designed guard installation parts (diagonal and arc shape) were fabricated for usability testing.

Table 1. Regression analysis on natural motion trajectories (height: 125, 155 cm)

Guard installation height (cm)	Linear regression	
	Trajectory*	Formula
155		$\hat{y} = 155.002 - 0.397x$ *Adjusted* $R^2 = 0.85$
125		$\hat{y} = 125.020 - 0.625x$ *Adjusted* $R^2 = 0.83$

* Predicted natural motion by regression function
Recorded natural motion by motion capture system

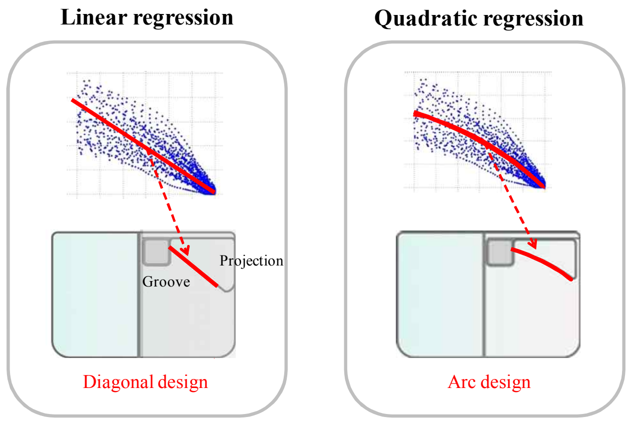
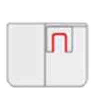
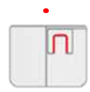
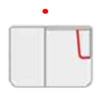
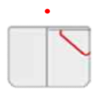
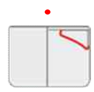


Figure 6. Product design using representative natural motion

Evaluating validity of new product

The validities of new designs were ergonomically evaluated using objective and subjective measures. In the case of validity evaluation, eighteen homemakers (average age: 43; SD = 7.7) participated and a two-factor (five guard shapes and six installation heights) within-subject design was used. The independent variables were guard shape (three existing designs: nipper shape w/o ARP, nipper with ARP, rectangular with ARP; two new designs: diagonal with ARP and arc with ARP; Table 2) and installation height (six levels: 15, 45, 75, 95, 125, and 155 cm; Figure 4). The objective measure was similarity of natural motion (average difference between natural motion trajectory and product-use motion trajectory of the product; unit: cm; Figure 7; equation 1) and the subjective measures include satisfaction (7- point scale; 1: very dissatisfied, 4: average, 7: very satisfied).

Table 2. Design alternatives for validity evaluation

Nipper (w/o ARP)	Nipper (with ARP)	Rectangular (with ARP)	Diagonal (with ARP)	Arc (with ARP)
				

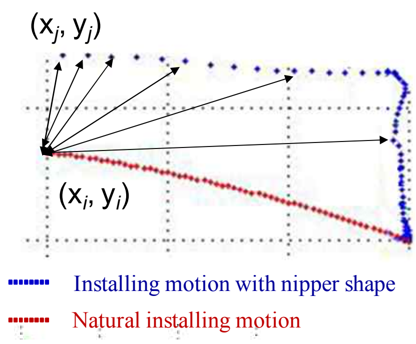


Figure 7. Diagram for the similarity of natural motion

$$D_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}$$

$$D_i = \min_j (D_{ij}) \qquad \text{(Equation 1)}$$

$$\overline{D} = \frac{\sum_{i=1}^{n} D_i}{n}$$

Where: i = 1 to n (n: number of data points of natural motion trajectory)

j = 1 to k (k: number of data points of product-use motion trajectory)

(x_i, y_i) = natural motion trajectory data point

(x_j, y_j) = product-use motion trajectory data point

D_{ij} = shortest distance between natural motion data point (i) and actual use motion data point (j)

D_i = shortest distance between natural motion data point (i) and actual use motion trajectory

$\overline{D}$ = average shortest distance between natural and actual use motion

VALIDITY EVALUATION

The new product designs based on natural motion can be evaluated in terms of user performance and preference. The present study evaluated the five different types of guard design (Table 2) on the different installation heights, and the differences between factor levels were statistically analyzed by ANOVA and Student-Newman-Keuls (SNK) test.

Similarity to natural motion

The similarities of natural motion among the different guard shapes were found significantly different (Figure 8). For instance, the use motions of new guard designs (diagonal and arc shape) were 0.8 cm closer to natural motion than those of existing ones ($F(4, 60) = 98.6$, $p < 0.001$; Figure 8). And significant differences between the designs with ARP design (1.6 cm) and those without ARP design (2.0 cm) were observed even though they had the same nipper shape.

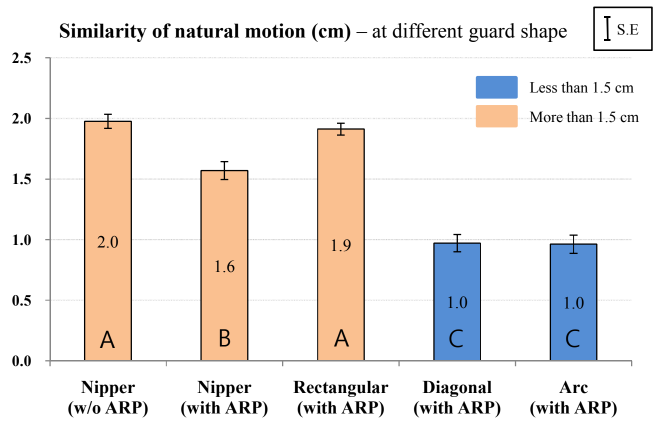


Figure 8. Similarity of natural motion

Task satisfaction

The satisfaction levels of the new guard designs were significantly higher than that of the existing ones ($F(4, 68) = 149.17$, $p < 0.001$; Figure 9). For example, the satisfaction levels of the diagonal and arc shape designs were 5.5 and 6.3 point, but that of the existing design (nipper shape) was only 3.3 point.

The satisfaction survey indicated that the ranked level of a guard design can be significantly affected by installation height ($F(5, 85) = 19.04$, $p < 0.001$). For instance, the satisfaction levels of guards from the pelvis height (75 cm) to the shoulder height (155 cm) were 5.3 point on average. On the other hand, those below the knee height (15 cm) and above the shoulder height (155 cm) were 4.4 point on average.

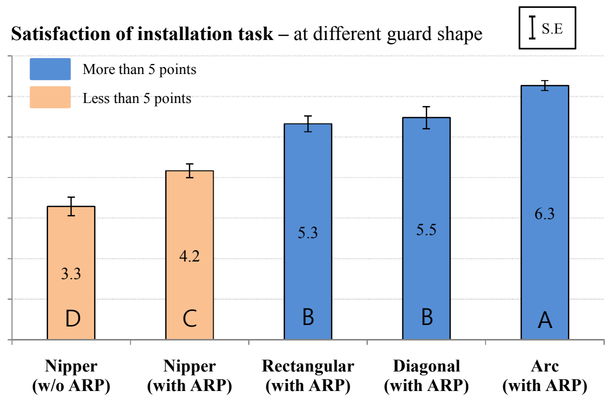


Figure 9. Task satisfaction

DISCUSSION

The present study proposed the quantitative analysis protocol of natural motion. Allie et al. (1999) and Nyberg and Kempic (2006) have suggested a comfortable seatback design and an ergonomic washing machine design by considering the users' preferred motion or posture. However, they did not describe the quantitative design procedure. The present study developed the natural motion analysis method and the regression method applied to analysis of the guard use motion.

To apply natural motion to product design, variability of natural motion needs to be evaluated for repeatability. In this study, the researchers defined natural motion as "comfortable and preferred movement during the product-use task". However, natural motion can be easily affected by unknown factors (e.g., experiment conditions, environment). So, the natural motions of every participant can have variability. Therefore, the supplementation of natural motion measurement protocol and motion variability analysis protocol (in terms of inter, intra-subject variability) are needed as future studies.

The proposed product design procedure based on natural motion can be widely used for product design. Previous motion analysis studies (Karlqvist et al., 1999; Moffet et al., 2002; Nelson et al., 2000) used motion as an evaluation measure of product. However, the present study used it as a parameter of product design. Likewise, the proposed method can be applied to any kinds of product designs (e.g., hand-held device: mobile phone, automobile component design, things of daily necessity).

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