The Ease of Grasping to Evaluate Aesthetically Pleasing PET Bottle Design*

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Abstract
The objective of this paper is to propose a method to evaluate an aesthetically designed product from the viewpoint of grasping. Ease of grasping, which is considered to affect the ergonomic aspect of aesthetic design, is estimated by using the moment of force in the hand when grasping the aesthetically designed product. Two grasping positions are used to evaluate the ease of grasp. These grasping positions are achieved when the hand exerts a minimum moment of force. A design support system was also developed based on the design method from the previous work and current proposed evaluation method. The system is capable of providing an aesthetic design solution and to subsequently perform the ease of grasping evaluation. The effectiveness of the proposed method was confirmed in ergonomics experiment using a PET bottle shape.

Key words: Aesthetic Design, Ease of Grasp, Ergonomic Aspect, Moment of Force

1. Introduction

With the rapid growth of technology, consumer requirements for everyday products are changing and becoming more diverse. Criteria such as appearance, ergonomics, and user friendliness have been incorporated into products to enhance their appeal. However, conventional CAD systems are ineffective at incorporating additional values during the product design stage due to their lack of functions for expressing shapes envisioned by the designer (1). Consequently, additional design steps are often required to improve the aesthetics of a product.

Kansei engineering can assess product appearance, but this method entails lengthy data acquisition and is thus not responsive to the very diverse range of consumer preferences. To overcome this weakness, other design methods (2)-(4) have been applied. The design method proposed in our previous study (4) adopts the Taguchi Method to efficiently determine stable design conditions with respect to the noise in customer emotions. The robust design focuses on bringing the mean closer to the desired target and simultaneously reducing the variation in quality. This method permits rapid identification of product parameters affecting consumer impressions.

Assessment of the ergonomics aspect is performed by using fundamental data that describe hand postures and forces generated by fingers (5)-(7). These data are obtained by employing actual models and ergonomic measurement systems. Endo et al. (8)-(10) proposed a new method that employed a digital hand to assess the ergonomics of a 3D digital model. Although the optimal grasping posture was difficult to determine, the ergonomic assessment was performed by determining hand coverage and posture on product casing through the use of digital data. This ergonomic assessment was evaluated by conducting interviews to determine subjects’ feelings when they mimicked the grasping postures obtained by using
the system. Such an evaluation can lead to bias and subjectivity. In contrast, the effect of product weight on ergonomics has not been assessed, even though product weight contributes to force-closure grasping. The objective of this paper is to propose a method for evaluating the aesthetic design from the viewpoint of ease of grasping. Ease of grasp is assumed to affect the ergonomic aspect of aesthetic design. A good design must enable the user to provide the ease of grasp, which is represented by the amount of force exerted while grasping the object.

It is important to integrate aesthetic design with ergonomic assessment to accelerate product development. In the present study, we developed a system for supporting aesthetic design and ergonomic assessment in a CAD system. We propose the ease of grasping to evaluate an aesthetically designed polyethylene terephthalate (PET) bottle shape by considering the product weight. In this paper, grasping is defined as the action of grasping an upright PET bottle and tilting it so that the liquid in the bottle flows into the mouth. As discussed in detail in Section 2.2, the selection of the grasping location is simplified by selecting two regions as grasping portions. The hand posture and finger position during grasping are described in Section 2.3. Evaluation of the ease of grasping is described in Section 2.4. In Section 3, a system is proposed to generate the aesthetically designed PET bottle shape and subsequently perform the ease of grasping evaluation of the proposed aesthetic design. The effectiveness of this system is evaluated in Section 4.

2. Methodology

2.1 Aesthetic design solution

Figure 1 shows a flow diagram of an interactive design support system based on the design method proposed in the previous study (4). First, the designer inputs the target value of four pairs of Kansei words (Adult-Childish, Ordinary-Stylish, Simple-Sophisticated, and Masculine-Feminine) and specifies the bottle volume and cross-sectional shape. The system automatically determines the appropriate optimum solution that corresponds to the target value. The optimum solution is determined from the signal-to-noise (S/N) ratio and the average output. Then, the system calculates the correspondence component score for the obtained value and maps the score to the appropriate design shape parameters. Finally, a parametric design for an aesthetic PET bottle shape can be obtained. The bottle shapes can be realized in the CAD system based on the design parameters.

2.2 Grasping portions

Two grasping portions are selected based on the following considerations:

a. Center of mass (COM) of the object

The torque that a user needs to apply to prevent an object from rotating is minimized at the COM. In this portion, the force closure required to counteract arbitrary forces and torques is the minimum. Moreover, grasping the object near its COM enables the user to readily control the force appropriately (11).

b. Narrow portion of the object

An object with a diameter in the range 20–30 mm allows the human hand to generate the maximum grasping force (12). Consequently, objects with diameters less than or greater than this range will be grasped with a lower grasping force. However, the optimum diameter is difficult to achieve in aesthetic PET bottle design. Moreover, the diameter of 20 mm to 30 mm is considered to be very small in PET bottle design. One approach is to grasp at the diameter closest to the optimum diameter. To address this problem, grasping at the bottle cross-section with the smallest diameter or cross-section is proposed.
Objects with diameters in the range 20–30 mm are likely to provide a suitable grasping posture because grasping an object with this diameter maximizes the contact area between the hand and the bottle. A greater contact area reduces the average pressure for a given normal force applied by the hand. Therefore, a greater contact area reduces the probability of discomfort or pain produced by the application of high pressures. In addition, a greater contact area between the skin and an object increases the friction coefficient (13). Thus, a greater contact area is preferable when friction force is applied. Such a portion corresponds to the narrow curved portion of the PET bottle.

2.3 Hand posture during grasping

Figure 2 illustrates the hand posture during the grasping considered in this paper. The origin is located at the base of the thumb. The grasping posture is generated when the outer surface of the index finger (indicated by the horizontal strip in Fig. 2) is in contact with the bottle surface corresponding to the grasping height; this action ensures that the hand grasps the bottle at the desired height.

The finger position during grasping is determined by the dimensions of the palm and fingers relative to the bottle diameter. The finger length is measured as the distance between the fingertip and the wrinkle line at the base of the middle finger. Kinoshita et al. (6) provided a set of hand anthropometry parameters for Japanese that includes the finger length. The palm length, which is defined as the distance between the wrinkles at the wrist and the wrinkles at the base of the middle finger, is calculated by the following expression:

$$pl = hl - mfl$$  \hspace{1cm} (1)

where \(pl\) denotes palm length, \(hl\) denotes hand length, and \(mfl\) denotes middle finger length. Except for the thumb, finger positions about the bottle when grasping a bottle are determined from the origin by the following expression:
where \( fp \) denotes finger position, \( fl \) denotes finger length, and \( i = 2, 3, 4, \) and 5 are the index finger, the middle finger, the little finger, and the ring finger, respectively. The thumb position when grasping is defined relative to the origin by the following expression:

\[
 tp = C - thl 
\]  

where \( tp \) denotes thumb position, \( C \) denotes bottle circumference, and \( thl \) denotes thumb length. The bottle radius for calculating the bottle circumference is approximated by cubic spline interpolation.

The bottle radius can be calculated by inputting the bottle height into the cubic spline function. The thumb and finger positions while grasping a bottle are illustrated in Fig. 3.

\[
 Radius_{(i)} = \text{cubicspline}_{(i)} 
\]

The thumb and finger widths are determined by the formula proposed by Buchholz and Armstrong\(^{(14)}\). The thumb and finger heights (see Fig. 4) are determined by the following:

\[
 thh = gh - (tw/2) 
\]

\[
 ih = gh - (iw/2) 
\]

\[
 mh = gh - (iw + mw/2) 
\]

\[
 lh = gh - (iw + mw + lw/2) 
\]

\[
 rh = gh - (iw + mw + lw + rw/2) 
\]

where \( thh \) and \( tw \) denote thumb height and width, respectively; \( ih \) and \( iw \) denote index finger height and width, respectively; \( mh \) and \( mw \) are middle finger height and width, respectively; and \( lh \) and \( lw \) are little finger height and weight, respectively. In addition, \( rh \) and \( rw \) denote ring finger height and width, respectively, and \( gh \) denotes the height of the grasping portion (i.e., near the COM, in the narrow or curved section of the bottle).

### 2.4 Force and moment of force to assess the ease of grasping evaluation

The ease of grasping evaluation is performed by applying Newton’s third law, Coulomb’s law, and the moment equilibrium to determine the forces and the moment of force at the fingers and thumb. Analogous with Newton’s third law, the total force for
grasping and lifting the bottle is expressed as follows:

\[ F_{\text{gravity}} = -F_{\text{grasping and lifting}} \]  

(10)

where \( F_{\text{gravity}} \) is the gravity force, and \( F_{\text{grasping and lifting}} \) is the total force required for grasping and lifting the bottle. The total force for grasping and lifting equals the sum of the individual forces generated by the thumb and fingers. Figure 5 illustrates the forces acting on the fingers when grasping the bottle. The grasping force consists of normal and friction forces. The normal forces of individual fingers and the thumb are determined as percentages of the total grasping force\(^6\). The friction forces for individual fingers and the thumb are determined based on Coulomb’s law of friction:

\[ F_{F(i)} = F_{N(i)} \times \mu_{s(i)} \]  

(11)

where \( F_{F(i)} \) denotes the friction force of the \( i \)th finger, \( F_{N(i)} \) denotes the normal force of the \( i \)th finger, and \( \mu_{s(i)} \) denotes the friction coefficient of the \( i \)th finger. The friction coefficient of human skin was approximated by Seo et al.\(^{15}\) as follows:
The moment of force is determined based on the principle of moment equilibrium, which states that the resultant moment acting on an isolated body must be zero:

\[ M_{(i)} = -F_{N(i)} \times X_{N(i)} - F_{F(i)} \times X_{F(i)} \]  

(13)

where \( M_{(i)} \) denotes the moment of force of the \( i \)th finger, \( X_{N(i)} \) denotes the distance between the application point of the normal force of the \( i \)th finger and the COM height, and \( X_{F(i)} \) denotes the distance between the application point of the friction force of the \( i \)th finger and the COM height. The subscripts \( i = 1, 2, 3, 4, \) and 5 denote the thumb, index finger, middle finger, ring finger, and little finger, respectively. \( X_{N(i)} \) is obtained from the thumb and finger heights given by eqs. (5)–(9), while \( X_{F(i)} \) is obtained by substituting the finger and thumb heights into eq. (4). By using the resultant force due to the inclination angle, the moment of force when grasping a bottle that is inclined at an angle can be determined.

3. Design Support System in CAD

3.1 Generation of aesthetically designed PET bottle shape

Section 2.1 described the theory for implementing the design method(4) for aesthetic design. This method is applied to obtain PET bottle shapes that satisfy the abovementioned four categories of consumer emotions: Childish-Adult, Ordinary-Stylish, Simple-Sophisticated, and Masculine-Feminine. The data of the principal loading matrix and the neural network optimum weights and biases are written as an array. The aesthetic PET bottle shape was designed in the following steps:

**Step 1:** Input aesthetic weights for four categories of emotions. Determine the optimum solution from the S/N ratio and average output arrays. Call the array of the principal loading matrix and calculate the principal component score based on the selected design parameters.

**Step 2:** Normalize the principal component score.

**Step 3:** Call the array of the neural network weights and biases. Map the principal component scores to the design parameters. Obtain design parameters that match the target value.

**Step 4:** Generate 2D sketches (ring fragments connected by a spline) of the PET bottle based on the design parameters obtained in step 3.

**Step 5:** Perform 3D solid blend protrusion for a 1-mm-thick shell on the solid model.
3.2 Ease of grasping evaluation

To perform ease of grasping evaluation based on the product (PET bottle) weight, a liquid model is required to model an actual liquid. The liquid model is a solid model representing the shape of the liquid inside the bottle. Figure 6 shows the method to generate an assembly of the PET bottle and the liquid model. The method is described as follows:

**Step 6:** Generate a 3D solid PET bottle model using the same algorithm as steps 4 and 5, except for the shell operation.

**Step 7:** Subtract the solid model obtained in step 6 from the solid model obtained in step 5.

**Step 8:** Set the material properties of the remaining model to be those of water.

**Step 9:** Save the remaining model as *liquid.sldprt*.

**Step 10:** Open the assembly document.

**Step 11:** Call *bottle.sldprt* and *liquid.sldprt* sequentially.

**Step 12:** Set the *bottle.sldprt* origin to coincide with the system origin. Perform the mate operation to the *liquid.sldprt* origin.

**Step 13:** Rebuild the assembled models.

The new model obtained from this assembly procedure has the following characteristics. The total mass of the assembled model is defined as follows:
\[ M = m_1 + m_2 \]  
\[ W = M \times g \]  

where \( M \) denotes the total mass of the assembled model, \( W \) denotes the total weight of the assembled model, and \( g \) denotes the acceleration due to gravity (9.81 m/s\(^2\)).

The grasping portions are determined in the following steps:

a. The user grasps the bottle near the COM

After the COM is known, the next step is to determine the point of contact in the assembly model of the PET bottle. The point of contact is the point where the bottle surface makes contact with the palm surface of the hand COM. To determine the point of contact on the bottle surface, a cubic spline approximation is utilized. A 2D point is sketched on the point of contact position. The thumb and finger positions and heights can be determined from the point of contact position. The procedure to determine the grasping position around the bottle COM is executed in the system as follows:

**Step 14** Determine the mass properties, particularly COM. Set the COM height as the grasping height. Sketch a point at the COM height as the origin. Determine the finger and thumb positions using eqs. (1) and (2) and finger and thumb heights using eqs. (5)–(9).

b. The user grasps the narrow, curved portion of the bottle

The information on the bottle’s narrow portion position can be derived by the cubic spline approximation. A point of contact is sketched on the position of the bottle’s narrow portion. The thumb and finger positions and heights can be determined from the point of contact position.

**Step 14** Extract the bottle minimum diameters from the cubic spline function in eq. (4). Sketch a point at the minimum diameter as the origin. Determine the finger and thumb positions by eqs. (1) and (2) and the fingers and thumb heights by eqs. (5)–(9).

Ease of grasping evaluation is performed by using the assembled model. The following steps describe the procedure for performing ease of grasping evaluation.

**Step 15** Obtain radii that correspond to the thumb and finger positions and heights by eq. (3).

**Step 16** Determine forces and moment of forces at the thumb and fingers by eqs. (11)–(13).

3.3 Automation in CAD

An intelligent tool is developed based on the proposed aesthetic design and ergonomic assessment principle. It is performed by an application programming interface (API). An API is a set of programming instructions, routines, protocols, and tools that software applications use to communicate with each other. Function calls that provide the linkage to the required subroutines for execution are written in an API. The API in SolidWorks uses Visual Basic in Microsoft Visual Basic for Applications (VBA) to write function calls. Since SolidWorks contains Microsoft VBA, processes can be performed by calling SolidWorks functions.

The algorithm for aesthetic and ergonomic design assessment is written in the SolidWorks API and is automatically executed after all the required data have been inputted. Automation of aesthetic design and ergonomic assessment speeds up the design process since all the required CAD tasks are automated. The output of the system is directly presented in CAD, which is convenient for performing subsequent design prior to mass production of the product.
4. Results and Discussion

4.1 System performance

The interface of the design support system for generating an aesthetically designed PET bottle shape and subsequently performing ease of grasping evaluation of the design is presented in Fig. 7. The process involves generating the aesthetic PET bottle shape and the liquid model, combining the bottle and liquid models, determining the two grasping portions, and evaluating ease of grasping using the force and the moment of force generated by the hand during grasping. A comparison of the grasping performances of two grasping portions is performed based on the moment of force during grasping. The automated process reduces the time required to generate an aesthetic PET bottle shape and to evaluate it from the viewpoint of ease of grasping.

For the evaluation of the system performance, five target values were inputted for the four pairs of Kansei words. The bottle volume and cross-sectional shape were also specified, and design parameters were obtained. The system generated a PET bottle shape that satisfied these inputs. The bottle model and liquid model were generated and assembled into a 3D model in SolidWorks.

Two scenarios were created: a bottle model assembled with a liquid model at 1) 75% of the total bottle volume and 2) 99% of the total bottle volume, as shown in Fig. 8. For each scenario, two grasping positions were determined, and 2D point sketches were sketched on...
Table 1 shows the calculated moment of force for the two grasping positions in the different scenarios. In this table, grasping at the bottle's narrow portion provides less moment of force in scenario 1, while grasping at the bottle COM provides less moment of force in scenario 2. The grasping position that provides a minimum moment of force is considered to increase the user's ease of grasping. Therefore, it can be inferred that the bottle model in scenario 1 (Fig. 8 (a)) suggests ease of grasping position when the bottle is grasped at the bottle's narrow portion. In contrast, the bottle model in scenario 2 (Fig. 8 (b)) suggests ease of grasping position is obtained when the bottle is grasped at its COM. It is observed that the different liquid volumes have different positions of the point of contact. In addition, different positions of the point of contact affect the moment of force exerted in the hand.

From the result, it can be observed that the aesthetic design can provide different ease of grasping positions depending on the amount of liquid. The evaluation method proposed in this paper emphasizes how customers can obtain ease of grasping in the aesthetically designed PET bottle shapes with regard to the liquid amount. This is an important point because in the case of the PET bottle, the amount of the liquid will decrease over time. Grasping at an inappropriate position will cause discomfort due to the forces exerted by its users. In addition, the aesthetically designed PET bottle comes in various shapes, which requires the users to fit their hands appropriately. By using the proposed method, therefore, the designer can approximate whether the designed PET bottle can provide ease of grasping.

4.2 Experiment validation

An experiment to verify the ergonomic assessment of the grasping portions was performed for the aesthetic model in Fig. 8. The aesthetic PET bottle model was generated by a rapid prototyping machine using acrylonitrile butadiene styrene (ABS) as the material. It was known that ABS has a friction coefficient and a bending coefficient that are different from those of PET. Nevertheless, the idea of the experiment was to evaluate the aesthetically designed bottle shape. In addition, it was assumed that the friction coefficient
of ABS and PET perform along a similar trend with respect to the grasping portions, and therefore, the friction coefficient can be presented by the equations applied in this study.

The bottle model was filled with water to a volume similar to that inputted into the system. The grasping portions were determined according to the grasping portions obtained from the system. Eight subjects (ages: 20–30 years) participated in the ergonomic assessment. According to Goldman\(^{16}\), eight subjects constitute the minimum number of subjects for satisfying the 5\% criteria. In the experiment, electromyograms were used to measure the muscle activity while grasping the bottle. According to Prabhu et al.\(^{17}\), brachioradialis is one of the muscles that provided good measurement during grasping by a macaque monkey. In this study, brachioradialis was selected as the measured muscle. The experiment was conducted by imitating similar conditions to those in Fig. 8 (b), which was five target points and a liquid volume that was 99\% of the bottle total volume.

First, the muscle activity when grasping at maximum power was measured. Then, the muscle activity when grasping the bottle at the two positions was also measured. Figure 9 shows the measurement result of muscle (brachioradialis) activity when grasping the bottle model at the two different grasping positions. The data presented in Fig. 9 are the measured muscle activity when grasping, relative to the maximum grasping power. A paired t-test was conducted to compare the mean of the two grasping positions. Using a 95\% confidence interval, it seems that significant differences occur in the muscle activity between grasping at COM (\(\mu = 0.0625\) V/s, \(\sigma = 0.00628\)) and the bottle’s narrow portion (\(\mu = 0.079\) V/s, \(\sigma = 0.01154\)) (\(t(7) = -4.943, p = 0.002\)). It is observed that grasping at the bottle COM requires less muscle activity; in contrast, grasping at the bottle’s narrow portion requires more muscle activity. Muscle activity has a proportional relation to the amount of moment of force working at the hand\(^{15}\). This indicates that less muscle activity correlates with a minimum moment of force, and vice versa. In conjunction with ease of grasping evaluation, the grasping position that provides a minimum moment of force is regarded to provide the user's ease of grasp. A comparison between the calculated moment of force in Table 1 and the ergonomic experiment in Fig. 9 for the aesthetic PET bottle model filled with liquid at 99\% of the total bottle volume (scenario 2) shows that the ergonomic experiment confirms the effectiveness of the system and the method. Both results show that for the given scenario, grasping the aesthetically pleasing PET bottle model at its COM provides ease of grasping, as shown by the lesser amount of the moment of force and the required muscle power. This result demonstrates the effectiveness of the system for determining the moment of force during grasping and for determining a grasping position that gives a good ease of grasping.
A relationship exists between the aesthetic design evaluation and the proposed evaluation. The bottle model generated by using the method has an aesthetic design. The determination of the point of contact positions in the bottle COM and the bottle’s narrow portion relies on the aesthetic design. For this reason, aesthetic design is very important to determine whether a grasping position can provide ease of grasping. Moreover, the result of ease of grasping evaluation indicates how the aesthetic design/shape can provide ease of grasping.

5. Conclusion

This paper describes a method to evaluate the aesthetically pleasing PET bottle models by using ease of grasping. The bottle model is evaluated from the viewpoint of ergonomic assessment. The moment of force resulted from the bottle weight is used as the basis of the evaluation. Two grasping positions are proposed to evaluate the aesthetic design. The determination of the grasping positions depends on the shape of the bottle model (aesthetic design). A grasping position with less moment of force indicates less effort needed to perform the grasping activity, and vice versa. The effectiveness of the proposed method is confirmed by an experiment producing good results.

In addition, a design support system was developed and integrated in a commercial CAD system. The system is capable of providing an aesthetic design solution and subsequently performing ease of grasping evaluation. The system is also capable of reducing the time, effort, and money required to perform the ergonomic assessment based on ease of grasping. Integrating the developed system with a commercial CAD system will improve the performance efficiency during the product design stage.

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