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Evaluation Function of Drinking Ease from Aluminum Beverage Bottles Relative to Optimum Bottle Opening Diameter and Beverage Type

Running title: Evaluation Function of Drinking Ease

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Abstract

In recent years, aluminum beverage bottles having screw tops with opening diameters of 28 and 38 mm have been launched in the Japanese market in keeping with the modern-day drinking habits of consumers. Although Japanese consumers are familiar with such bottles, a majority of them feel that the 28 mm opening is too small and the 38 mm opening is too large. Therefore, we felt the need to develop a method for evaluating consumer feelings when they drink a beverage directly from the bottle opening. For this purpose, we propose an evaluation function of drinking ease that calculates the optimum opening diameter of the bottle. From results of our previous study, we know that there exists an ideal volume of beverage flowing into the mouth, at which consumers feel most comfortable while drinking directly from bottles. Therefore, we define the evaluation function of drinking ease in terms of the difference between the actual volume of fluid in the mouth and the expected ideal volume. If this difference is small, consumers probably feel comfortable while drinking the beverage. We consider a design variable, i.e., the opening diameter, and two state variables, i.e., the volume of beverage remaining in the bottle and the height of consumers, and construct the response surface of the evaluation function by using radial basis function networks. In addition, for investigating the influence of beverage type on the evaluation function, we select green tea and a carbonated beverage (Coke) as test beverages. Results of optimization of the proposed function show that when the opening diameters are 35.4 mm and 34.4 mm in the case of green tea and Coke, respectively, the actual volume of fluid in the mouth is closest to the ideal volume and the participants feel most comfortable drinking the beverage. These results are in agreement with results of our previous study that an opening diameter of 33 mm is optimum for young Japanese adults. Thus, we confirm that the proposed function is accurate; it can be used to design bottle openings to suit consumers of various age groups and types of beverages.

Keywords: Ergonomics, Drinking ease, Optimization, Aluminum beverage bottle

1. Introduction

Decisions taken by consumers while they are purchasing products are affected by key factors such as product usability, design novelty, and conformity with present-day trends in addition to rudimentary factors such as functionality, performance, and price. Therefore, to ensure that their products are accepted in the marketplace, product manufacturers are expected to incorporate consumers' sensibilities and preferences into their designs, rather than banking on product performance alone. From the viewpoint of a universal design of products, it is important to design products that can be used comfortably by people of all ages and genders. The science of ergonomics is applied to the design of products such as automobiles, man-machine interfaces of computers, and commodities. In particular, it is essential to apply ergonomics to the design of commodities such as beverage or food containers, clothes, and shoes, because consumers of all ages and genders use these commodities. In the past, ergonomical universal designs have been applied to beverage and food containers and are expected to enhance consumer convenience (Lewis et al., 2007; Yoxall and Janson, 2007; Carus et al., 2006). Anticipated benefits of ergonomically designed beverage and food containers include improved shelf life (length of time for which packaged food can be stored), visual appeal, and price.

Aluminum beverage bottles having screw tops with diameters of 28 mm and 38 mm were launched in the Japanese market in 2000 in keeping with the modern-day drinking habits of consumers; therefore, consumers are now familiar with bottles of these dimensions. Usually, consumers drink beverages in one of several ways: directly from the bottle opening, using a straw, or from a glass. Because aluminum beverage bottles can be resealed, consumers often carry them outdoors and drink directly from the bottle opening. It is, therefore, important for manufacturers of aluminum beverage bottles to design bottles after thoroughly considering the satisfaction levels of consumers drinking directly from the bottle opening. However, these dimensions were not designed on the basis of drinking satisfaction. To ensure survival in a competitive market, of course, it is important for manufacturers of aluminum beverage bottles to improve the usability of a part that is used without difficulty such as drinking satisfaction in addition to that of awkward part. Therefore, it is essential to develop a method for evaluating consumer feelings while they are drinking a beverage directly from the bottle opening and then determine the optimum opening diameter size for ensuring consumers' drinking satisfaction.

In previous studies (Yamazaki et al., 2007; Chihara et al., 2009), we investigated the effects of three bottle opening diameters—28, 33, and 38 mm—and beverage types—green tea and a carbonated beverage (Coke)—on human feelings in order to improve the comfort level of consumers drinking directly from the opening of aluminum beverage bottles and to determine the physical aspect that affects drinking satisfaction. Fig. 1 shows three test bottles with opening diameters of 28 mm, 33 mm, and 38 mm. In these studies, we asked consumers to complete a questionnaire on their drinking satisfaction; factor analysis results of the questionnaire showed that the drinking satisfaction is affected by two factors— the volume of fluid in the mouth before swallowing (hereafter referred to as "volume of fluid in the mouth") and flow rate adjustability. In addition, from a statistical analysis of the result of the questionnaires and a three-dimensional (3D) fluid dynamics analysis, we determined that there exists an ideal volume of fluid in the mouth for which participants feel comfortable while drinking from the bottle opening. Moreover, we confirmed that the 33 mm diameter is the best among the three diameters for Japanese young adult consumers irrespective of the beverage type. However, in these previous studies, we just compared the drinking satisfaction for the three diameters and did not determine the precise optimum diameter that would result in drinking satisfaction of consumers. We can compare the comfort levels of consumers in more detail by increasing the bottle diameters to generate more samples, e.g., increments of 1 mm from 28 to 38 mm; however, this would greatly increase the experimental cost. Thus, it is essential to develop a method for formulating the evaluation function of drinking ease that can be approximated by fewer experiments and evaluate the drinking satisfaction quantitatively. Therefore, the objectives of the present study were to formulate the evaluation function and determine the optimum diameter. The proposed evaluation function will provide designers detailed information on the drinking satisfaction of consumers and aid them in decision making for designing suitable products.

Structure optimization techniques based on finite element analysis (FEA) have been employed for the development of two-piece aluminum beverage cans and bottles with the aim of achieving better performance under various loading conditions. For instance, the lid can be made lightweight to prevent the bottle from being damaged by buckling and to maximize the strength of the bottle bottom against axial loads and internal pressure (Yamazaki et al., 2007; Han et al., 2005). In addition, such techniques have also been applied to develop PET bottles to make them lightweight and collapsible under a normal load by a human subject to the constraint of the buckling strength (Masood and KeshavaMurthy, 2005). Further, the shape optimization method has been applied to the prediction of optimal preform geometry or parison thickness distribution of plastic bottles in order to ensure their conformance to the required thickness distribution (Thibault et al., 2007; G.-Q. Huang and H.-X. Huang, 2007). However, these researches formulated and optimized only the mechanical function of beverage containers and not the evaluation function of consumer satisfaction.

Design methods for determining consumers' satisfaction, for example, drinking ease, and for maximizing their satisfaction have not been investigated thus far. Results of our previous studies show that drinking ease is governed by the following factors: fluid volume and flow rate adjustability. Therefore, for determining the optimum opening diameter, we derived an evaluation function of drinking ease, which involved the evaluation of the volume of fluid in the mouth and flow rate adjustability. In this study, we derive an evaluation function of drinking ease and optimize it. For investigating the influence of beverage type on drinking ease, we select green tea and a carbonated beverage (Coke) as test beverages. In this paper, first, we define the response surface of the evaluation function by using radial basis function networks (RBFNs). Then, we optimize the derived evaluation function and discuss whether it can yield the optimum opening diameter for drinking ease. Furthermore, we discuss whether the optimal opening diameter depends on the beverage type.

2. Evaluation Function of Drinking Ease

2.1 Definition of evaluation function of drinking ease

As mentioned previously, we have confirmed that there exists an optimum volume of fluid in the mouth for which participants feel comfortable while drinking directly from the bottle opening. This result is in agreement with the fact that drinking ease is dependent on the factor of fluid volume, as determined from the factor analysis. However, the actual volume of fluid in the mouth from the bottles is not always equal to the expected ideal volume (described in detail in section 2.5). Therefore, we define the evaluation function of drinking ease in terms of the difference between the actual volume of fluid in the mouth and the expected ideal volume. It is obvious that the smaller this difference, the closer is the actual volume to the ideal volume.

The fluid volume changes with a change in the drinking actions of consumers, e.g., inclination angle of the bottle. In addition, drinking actions of consumers do not always have constant values. Therefore, the fluid volume is probably different for different drinking actions. Therefore, we consider flow rate adjustability to be expressed in terms of the uncertainty of drinking actions and the considerable variation in the fluid volume, owing to this uncertainty. That is, we consider the variation of the “actual volume of fluid in the mouth,” which is a part of the definition of the evaluation function, based on the uncertainty of drinking actions so as to express flow rate adjustability.

2.2 Selection of design and state variables

Next, we consider the kinds of variables that should be used for formulating the evaluation function of drinking ease. The bottle opening diameter and the volume of beverage remaining in the bottle (hereafter referred to as the “volume of remaining beverage”) probably affect the volume of the fluid flowing out from the bottle opening. In addition, differences in types of consumers (hereafter referred to as “individual differences”), for example, their body dimensions, may also affect the fluid volume. Therefore, we must consider these three variables in order to define the evaluation function. Thus, we evaluate the relationship between the volume of fluid in the mouth and body dimensions.

We performed an experiment in which participants were 14 Japanese university students, including 4 females. We measured the volume of fluid in the mouth when the participants drank from the bottles. Three different test bottles with opening diameters of 28 mm, 33 mm, and 38 mm were used; these bottles had a maximum capacity of 300 ml and they were filled with 100 ml, 200 ml, and 300 ml of the beverage. As shown in Fig. 2, all participants were seated while drinking and were required to drink one mouthful of beverage. We also measured the body dimensions of the participants. We predicted that the dimensions of the mouth (mouth breadth and lip height) would affect the volume of fluid in the mouth. Further, because the height of the participants is one of the characteristic body dimensions, we measured the body height of the participants in addition to their mouth breadth and lip height, as shown in Fig. 3

(National Institute of Bioscience and Human-Technology, 1966).

Fig. 4 shows the relationship of the volume of fluid in the mouth with the mouth breadth, lip height, and body height. In this figure, r denotes the correlation coefficient between the body dimension and the volume of fluid in the mouth. From the figure, it is clear that the mouth breadth and lip height are only weakly correlated with the volume of fluid in the mouth. In contrast, the body height is strongly correlated with the volume of fluid in the mouth. The correlation of the body height with the volume of fluid in the mouth is significant at a 1% significance level. Thus, we use the body height as the representative variable of individual differences.

2.3 Formulation of evaluation function of drinking ease

We define the evaluation function of drinking ease by considering the following three variables: bottle opening diameter, volume of remaining beverage, and body height. Among these variables, the bottle opening diameter is the only design variable. The other two variables are state variables that fluctuate in a confined range. Hence, we must define the evaluation function as a function that evaluates the opening diameter in a given range of state variables. Therefore, we define the evaluation function as follows:

$$F(x_1) = \int_{x_{2\min}}^{x_{2\max}} \int_{x_{3\min}}^{x_{3\max}} \{O(x_1, x_2, x_3) \cdot P(x_3)\} dx_3 \, dx_2 \tag{1}$$

where x_1, x_2, and x_3 denote the bottle opening diameter, volume of remaining beverage, and body height, respectively. $x_{2\min}$ and $x_{2\max}$ are the minimum and maximum bounds of the volume of remaining beverage, and $x_{3\min}$ and $x_{3\max}$ are the minimum and maximum bounds of the body height, respectively. $P(x_3)$ is a weight function based on the distribution of height. From a statistical data (National Institute of Bioscience and Human-Technology, 1966), the distribution of height on Japanese subjects is shown in Fig. 5, if it follows a normal distribution. We apply the distribution of height as a weight function.

$O(x_1, x_2, x_3)$ is the response surface of the output predicted using the RBFN, which is one of the response surface methods. The detailed procedure for constructing a response surface using the RBFN is provided in the Appendix. Response surface methods approximate functional spaces globally by using m pairs of the input vector and output value ($\boldsymbol{x}_p$, y_p) (p = 1, 2, ⋯,m), where $\boldsymbol{x}_p = (x_{p1}, x_{p2}, \cdots, x_{pm})$ is the input vector and y_p is the output value. The response surface is written as follows:

$$\hat{y} = \sum_{p=1}^{m} w_p \phi_p (\boldsymbol{x}_p) \tag{2}$$

where $\hat{y}$ denotes the predicted response surface and w_p and ϕ_p are the weight parameter and basis function, respectively. In this study, the bottle opening diameter, volume of remaining beverage, and body height are considered as the input values, and the difference between the actual volume of fluid in the mouth and the expected ideal volume is the output value for predicting the response surface by using the RBFN. Thus, the response surface gives the difference between the volume of fluid in the mouth and the corresponding ideal volume. The smaller the value of $F(x_1)$, the closer is the actual fluid volume to the expected ideal volume of fluid in the mouth.

2.4 Consideration of flow rate adjustability

The volume of fluid in the mouth probably changes with a change in the drinking actions of consumers. In order to account for the variability of the volume of fluid in the mouth while deriving the evaluation function, we define the input values of the training data of the RBFN as follows:

$$y_{ijk} = \int_{x_{4\min,k}}^{x_{4\max,k}} \int_{x_{5\min}}^{x_{5\max}} \left\{ w\left(V_{ijk}\right) \cdot P_{x_4,ijk}\left(x_4\right) \cdot P_{x_5,ijk}\left(x_5\right) \right\} dx_5 \, dx_4 \tag{3}$$

where y_{ijk} denotes the integrated difference between the volume of fluid in the mouth in consideration of its variation and the ideal volume over the entire range of drinking actions. In addition, i, j, and k denote the i-th participant, j-th opening diameter, and k-th volume of remaining beverage, respectively; x_4 denotes the final inclination angle of the bottle when a participant drinks the beverage; and x_5 is the time duration in which the inclination angle of the bottle changes from the initial angle to the final angle. As shown in Fig. 6, we define the inclination angle of the bottle as the acute angle between the horizontal plane and the central axis of the bottle. In order to determine representative variables of the drinking actions of consumers, we recorded the drinking actions of several participants with a video recorder and measured the inclination angle of the bottle. In this experiment, we used bottles with an opening diameter of 33 mm; its maximum capacity was 300 ml, and it was filled with 100 ml, 200 ml, and 300 ml of the beverage. Fig. 7 shows an example of the history plots of the inclination angle. Fig. 7 and the results of the other participants show that the rotation velocities of the bottles are almost constant when they drink beverages directly from the bottle opening. Therefore, for simplicity, we assume that the rotation velocity of the bottle is constant and use the final inclination angle and the abovementioned time duration as representative variables of the drinking actions of participants. $x_{4\min,k}$ and $x_{4\max,k}$ in Eq. (3) denote the minimum and maximum values, respectively, of the final inclination angle. Similarly, $x_{5\min}$ and $x_{5\max}$ denote the minimum and maximum values, respectively, of the time duration. We set different final inclination angles corresponding to each volume of remaining beverage, because the final inclination angle depends on this volume.

In Eq. (3), $w(V_{ijk})$ denotes the weight function of comfort, which will be described in detail in the next subsection; this function represents the comfort level of the volume of fluid in the mouth. $w(V_{ijk})$, which includes V_{ijk}, i.e., the actual volume of fluid in the mouth in consideration of its variation, is given as follows:

$$V_{ijk} = \overline{V}_{ijk} + \Delta V_{ijk}\left(x_4, x_5\right) \tag{4}$$

where $\overline{V}_{ijk}$ denotes the average of the volume of fluid in the mouth. $\Delta V_{ijk}(x_4, x_5)$ is the change in the volume of fluid in the mouth because of the uncertainty of the drinking actions, and it is given by the following equation:

$$\Delta V_{ijk}\left(x_4, x_5\right) = Q\left(x_1, x_2, x_4, x_5\right) - Q\left(x_1, x_2, \overline{x}_{4,ijk}, \overline{x}_{5,ijk}\right) \tag{5}$$

Here, $Q(x_1, x_2, x_4, x_5)$ is the fluid volume function that gives the fluid volume from the bottle opening. In the following subsection, we describe how to approximate $Q(x_1, x_2, x_4, x_5)$. $\overline{x}_{4,ijk}$ and $\overline{x}_{5,ijk}$ are the average values of the final inclination angle and time duration, respectively. Therefore, Eq. (4) expresses the volume of fluid in the mouth in consideration of its variation owing to the uncertainty of drinking actions.

Let $P_{x_4,ijk}\left(x_4\right)$ and $P_{x_5,ijk}\left(x_5\right)$ denote the probability density functions of the final inclination angle and time duration, respectively, obtained by the assumption that the drinking actions follow a normal distribution; they are given by

$$P_{x_4,ijk}(x_4) = \frac{1}{\sqrt{2\pi}\sigma_{x_4,ijk}} \exp\left\{ -\frac{\left(x_4 - \bar{x}_{4,ijk}\right)^2}{2\sigma_{x_4,ijk}^2} \right\} \quad (6)$$

$$P_{x_5,ijk}(x_5) = \frac{1}{\sqrt{2\pi}\sigma_{x_5,ijk}} \exp\left\{ -\frac{\left(x_5 - \bar{x}_{5,ijk}\right)^2}{2\sigma_{x_5,ijk}^2} \right\} \quad (7)$$

where $\sigma_{x_4,ijk}$ and $\sigma_{x_5,ijk}$ are the standard deviations of the final inclination angle and time duration, respectively.

Hence, the smaller the value of Eq. (3), the closer is the volume of fluid in the mouth to the ideal volume over the entire range of uncertainty of drinking actions.

2.5 Approximation of weight function of comfort

We performed an experiment to determine the ideal fluid volume for a single swallow and subsequently determine the expected ideal volume of fluid in the mouth and approximate $w(V_{ijk})$. The participants in the experiment were six university students (three males and females each). We measured the myoelectric potentials of participants' throats (sternohyoid muscle) when they swallowed water. This muscle is involved in the action of swallowing (Nagatani, 2004). The myoelectric potentials were measured, at a sampling frequency of 1000 Hz, by attaching surface electrodes (DE–2.1, DELSYS Inc.) to the measurement positions; the measured potentials were then stored in a computerized record after amplification (Bagnoli–2, DELSYS Inc. and UAS–108S, UNIQUE MEDICAL Co., Ltd.). The participants were required to drink water in a single swallow, and the volume of water was increased in 5-ml increments from 5 to 30 ml. The measurement was performed two times for each volume. The measured myoelectric potentials were integrated from the beginning to end of muscle contraction. The integrated myoelectric potentials were divided by the time elapsed from the beginning to the end of muscle contraction (hereafter referred to as "mean amplitude of the myoelectric signal").

Fig. 8 shows the result of the experiment. The mean amplitudes of the myoelectric signal were normalized for each participant by using the following equation:

$$\overline{M}_i = \frac{M_i - M_{\min,i}}{M_{\max,i} - M_{\min,i}} \quad (8)$$

where i denotes the i-th participant; in addition, $\overline{M}_i$ and M_i denote the normalized mean amplitude and mean amplitude, respectively. $M_{\max,i}$ and $M_{\min,i}$ are the maximum and minimum, respectively, of the mean amplitude of the i-th participant. The mean amplitudes are normalized within the range of 0 to 1 for each participant by Eq. (8). The mean amplitudes of all participants are plotted together in Fig. 8. As seen from this figure, the normalized mean amplitude of the myoelectric signal can be regarded as a quadratic function of the swallowed volume. Hence, $w(V_{ijk})$ can also be regarded as a quadratic function of the swallowed volume by assuming that the mean amplitude of the myoelectric signal is correlated with the comfort level of swallowing. In addition, the approximate function shown in

Fig. 8 reaches the minimum at approximately 16 ml, which is similar to the result of a previous study that reported the optimum value of an average swallow for 136 Japanese individuals to be approximately 18 ml (Miyaoka et al., 2000). Thus, we assume that the ideal fluid volume of18 ml for a single swallow is more reliable than our result of 16 ml. Then, we consider the ideal volume of fluid in the mouth to be a multiple of 18 (ml), because there is a possibility of consumers swallowing in plural divided one volume of fluid in the mouth when they drink. In other words, the difference between multiples of 18 ml that are closest to the actual fluid volume and the actual fluid volume is used as the ideal volume of fluid in the mouth (see Fig. 9). The weight function $w(V_{ijk})$ is given by the following equation:

$$w\left(V_{ijk}\right)=\frac{1}{18^2}\left(V_{ijk}-V_{\mathrm{ideal}}\right)^2 \tag{9}$$

Here, V_{ideal} denotes the ideal volume of fluid in the mouth. Initially, the weight function of comfort, $w(V_{ijk})$, reaches a maximum ($w(V_{ijk})$ = 1.0) at 0 ml and minimum ($w(V_{ijk})$ = 0.0) at multiples of 18 ml. When the volume of fluid in the mouth increases, consumers probably swallow in plural divided the fluid, because it is hard to swallow a large volume of beverage at once. Therefore, if the volume of fluid in the mouth becomes relatively large, $w(V_{ijk})$ should be calculated for each divided volume of fluid for a single swallow. However, it is difficult to measure or determine the divided volume of fluid for a single swallow when consumers swallow in plural divided the volume of fluid in the mouth. Hence, we adjust $w(V_{ijk})$ as a function that reaches a minimum at multiples of 18 ml under the assumption that the ideal volume of fluid for a single swallow is 18 ml and continues at the intermediate between multiples of 18 ml (see Fig. 10).

The ideal volume of fluid for a single swallow may not be a unique value; it may vary with anthropometric dimensions such as body height. In addition, the ideal volume of fluid for a single swallow is affected by the style of drinking, such as drinking in one gulp and sipping. However, it is difficult to assemble a large number of participants for the experiments and to determine an optimum volume; furthermore, it is difficult to classify and specify the drinking style in detail. Hence, we assume the ideal volume of fluid in the mouth to be a constant value that is a multiple of the ideal volume of fluid for a single swallow. In addition, in the measurement of volume of fluid in the mouth, which is shown in section 3.1, we just asked the participants to drink one mouthful of beverage and did not give them any other instructions on how to drink.

2.6 Approximation of fluid volume function

We used the response surface methodology based on design of experiments (DOE) (Myers and Montgomery, 1995) to approximate $Q(x_1, x_2, x_4, x_5)$. We determined a combination of variables, i.e., the bottle opening diameter, volume of remaining beverage, final inclination angle, and time duration, by using an orthogonal array of the DOE. Then, we performed 3D fluid dynamics simulations at sampling points based on the orthogonal array by using the analysis code FIDAP (Fluent Inc.), under the same analysis conditions as those in our previous study (Chihara et al., 2009).

First, we carried out a factorial analysis in which each variable has two levels, on the basis of the measurement result of participants' drinking actions, so as to investigate the interaction among four variables—the bottle opening size x_1; the volume of remaining beverage, x_2; the final inclination angle x_4; and the time duration x_5. Results of the analysis of variance of the four variables showed that three combinations of interactions—x_1 and x_4, x_1 and x_5, and x_4 and x_5—had statistically significant differences; thus, the four variables were assigned to the L_{27} orthogonal array of the DOE, so that these three combinations would be considered. In addition, we found that the final inclination angle was dependent on the volume of remaining beverage; hence, we set the levels of the final inclination angle as follows:

Lower limit of x_4: (Intermediate value of x_4) – 12.5°
Intermediate value of x_4: ((–3x_2/20) + (65/2))°
Upper limit of x_4: (Intermediate value of x_4) + 12.5°

Further, the ranges of the other variables (x_1– x_3) are given by

$$\begin{aligned} 28.0 \le x_1 \le 38.0 \\ 100 \le x_2 \le 300 \\ 1.70 \le x_5 \le 5.00 \end{aligned} \tag{10}$$

The L27 orthogonal array is presented in Table 1. As mentioned earlier, $Q(x_1, x_2, x_4, x_5)$ was obtained by the use of the response surface methodology. Further, the response surface was approximated using a quadratic polynomial that includes cross terms, as follows:

$$\begin{aligned} &Q(x_1, x_2, x_4, x_5) = -1.27\times10^2 + 1.12x_1 - 3.79\times10^{-2}\left(x_1 - 3.30\times10^1\right)^2 \\ &+ 4.25\times10^{-1}x_2 - 2.98\times10^{-4}\left(x_2 - 2.0\times10^2\right)^2 + 2.73x_4 + 7.70\times10^{-2}\left(x_4 + 1.50\times10^{-1}x_2 - 3.25\times10^1\right)^2 \\ &+ 7.97x_5 - 1.50(x_5 - 3.35)^2 + 7.13\times10^{-2}\left(x_1 - 3.30\times10^1\right)\left(x_4 + 1.50\times10^{-1}x_2 - 3.25\times10^1\right) \\ &- 1.31\times10^{-1}\left(x_1 - 3.30\times10^1\right)(x_5 - 3.35) + 6.18\times10^{-1}\left(x_4 + 1.50\times10^{-1}x_2 - 3.25\times10^1\right)(x_5 - 3.35) \end{aligned} \tag{11}$$

3. Results of optimization and discussion

3.1 Measurement of volume of fluid in the mouth and recording of drinking actions

In our experiments, we asked the participants to drink one mouthful of beverage and measured the volume of fluid in the mouth when they drank directly from the bottle. Further, in order to measure the final inclination angle and the time duration of rotation, we recorded the drinking actions of the participants by using a video recorder. We performed an experiment in which the participants were 12 Japanese university students, including 4 females. The bottle was filled with 100 ml, 200 ml, and 300 ml of green tea and Coke. In this experiment, the opening diameters and capacities of the test bottles were the same as those mentioned in subsection 2.2. We performed the measurement three times under each experimental condition. All participants were asked to rank the three kinds of bottles (28, 33, and 38 mm opening diameters) in the order of drinking ease for each volume of remaining beverage so as to determine their preference of opening size. We also queried the participants on their thirst level and preference for beverages before the measurement and confirmed that none felt excessive thirst and that none disliked green tea and Coke.

3.2 Results of optimization

We formulated Eq. (1) using the data obtained from the measurement of the volume of fluid in the mouth and recording of drinking actions; then, we minimized Eq. (1). The upper and lower bounds of the design and state variables are given as

$$
\begin{aligned}
28 &\le x_1 \le 38 \\
100 &\le x_2 \le 300 \\
1610 &\le x_3 \le 1820
\end{aligned}
\tag{12}
$$

Fig. 11 shows the evaluation functions of drinking ease for green tea and Coke. Table 2 lists the ranking results for green tea and Coke, as submitted by all participants. In all, 36 rankings were collected (12 participants × 3 volumes of remaining beverage). With 3 points given to the first rank, 2 points to the second, and 1 to the third rank, the total ranking scores of the three kinds of bottles were calculated as shown in the last column of Table 2. Fig. 11 shows that the optimum value in the case of green tea is obtained at x_1 = 35.4 mm, whereas that in the case of Coke is obtained at x_1 = 34.4 mm. The optimum opening diameter for Coke is smaller than that for green tea; however, the difference is only about 1 mm.

From Table 2, it is found that in the case of green tea, the scores of the 33 mm and 38 mm openings are almost the same, whereas in the case of coke, the 33 mm opening shows the highest score and the 38 mm opening has the second highest score. The values of the evaluation function in the case of green tea, shown in Fig. 11, are almost the same at 33 mm and 38 mm. In contrast, in the case of Coke, the value at 33 mm is smaller than that at 38 mm. Therefore, the qualitative trend of evaluation function agrees with the participants' subjective satisfaction.

Fig. 12 shows evaluation functions for different ranges of body height in the case of (a) green tea and (b) Coke. These ranges are short ($1610 \le x_3 \le 1680$), average ($1680 \le x_3 \le 1750$), and tall ($1750 \le x_3 \le 1820$). Then, we minimize the evaluation functions and obtain the optimum opening diameters, listed in Table 3. From Fig. 12 and Table 3, it is found that the taller the participant, the larger is the optimum opening diameter in the case of green tea. The difference between the optimum diameters in the short and tall ranges is about 4 mm in the case of green tea. On the other hand, the difference in the case of Coke is only about 1 mm; thus, the optimum opening diameter is more affected by the height of participants in the case of green tea than in the case of Coke.

3.3 Discussion

We consider that the evaluation function formulated in Eq. (1) is valid for expressing the drinking satisfaction, because its qualitative trend agrees with the participants' subjective satisfaction. Result of the optimization of the evaluation function of drinking ease and the fluid volume from openings with a diameter of 35.4 mm (in the case of green tea) and a diameter of 34.4 mm (in the case of Coke) are possibly the closest to the ideal volume of fluid in the mouth; participants reported ease of drinking at these diameters in the ranges mentioned in Eq. (12). In addition, the preferred opening diameter for Coke is smaller than that for green tea. This may be explained by the fact that carbonated beverages have a foaming tendency, and when the opening diameter is relatively small, the fluid volume is small, thereby making it easy for the drinker to adjust the flow and thus feel comfortable. This is in agreement with the result of our previous study that the factor of flow rate adjustability is more significant than the volume of fluid in the mouth in the case of carbonated beverages. However, the difference in the optimum opening diameters for green tea and Coke was only about 1 mm; hence, it was observed that the beverage type did not strongly affect the optimum opening diameter in the case of these participants.

From Fig. 12 and Table 3, we can conclude that taller participants prefer larger opening diameters while drinking green tea; on the other hand, opening diameter does not strongly affect the drinking satisfaction of participants drinking Coke. This is because in the case of green tea, getting the desired volume is more important than adjusting the flow. That is, the taller participants tend to drink a large volume of beverage in a mouthful; therefore, when they drink green tea, they prefer a larger opening diameter that permits a larger volume of beverage to flow into the mouth.

From a comparison between evaluation functions for different ranges of heights, it is obvious that the drinking satisfaction is worse in the case of a relatively small opening diameter irrespective of the beverage type and participant height. On the other hand, in the case of green tea, the relatively large opening diameter does cause the drinking satisfaction to worsen for the "short" range participants. Thus, the drinking satisfaction is not very low irrespective of the beverage type and height of participants around the neighborhood of the optimum opening diameters (approximately 34 to 36 mm). Therefore, we conclude that perhaps the optimum diameter, which is obtained by optimizing the evaluation function, is a robust solution for beverage type and the height of the participants.

4. Conclusions

In this study, we have proposed an evaluation function of drinking ease, which considers the volume of beverage flowing into the drinker's mouth and flow rate adjustability, for determining the optimum opening diameter for drinking ease. We have also optimized the evaluation function by performing experiments and found that the volume of beverage consumed by the participants is closest to the ideal volume of fluid in the mouth and their comfort level is highest when the bottle opening diameter is 35.4 mm in the case of green tea and 34.4 mm in the case of Coke. It should be noted that the optimum opening diameters are only for these participants. Both these optimal opening diameters are around 33 mm, which is in agreement with the result of our previous study that the opening diameter of 33 mm is best suited for Japan's young adult consumers irrespective of the beverage type. Thus, these optimum opening diameters appear to be accurate, and we believe that the proposed evaluation function may provide quantitative information on drinking ease, which is actually a qualitative feeling. Thus, we have used the proposed function to determine the optimum bottle opening diameter from which consumers can comfortably drink an optimum volume of beverage (i.e., drinking ease). Moreover, results of optimization of the evaluation function have shown that the optimal opening diameter for drinking ease depends on the beverage type. Therefore, manufacturers of aluminum beverage bottles should design the dimensions of bottle openings by considering the beverage type, thus ensuring the comfort and satisfaction of consumers. We have also found that the optimal opening diameter depends on individual differences, e.g., the height of consumers. Thus, the proposed evaluation function can be used to determine the optimum opening diameter of bottles that are to contain beverages targeted at a particular category of consumers.

Although we had intended to include participants of all age groups in this study, only young students readily consented to participate because it was easy to ask them to be the participants. However, for designing a bottle opening from which consumers of all age groups and genders achieve drinking satisfaction, it is essential to consider a broad range of ages of participants of the study; in particular, children should participate in such a study. If, as concluded in the study, body height is one of determining factors for the optimum opening diameter, the diameter for children probably varies much more than that for adults. Perhaps the optimum opening diameter for the drinking satisfaction of children will be smaller than that for adults. Drinking satisfaction is affected by the following design variables: opening diameter and the material and shape of the bottle. Across the range of bottles presently available in the market, the material and shape hardly differ, because of the ease of recycling and the forming process of the current material and. Therefore, we focus on the effect of the cap diameter, which is relatively easy to change, on drinking satisfaction. In addition, perhaps the drinking satisfaction is affected by factors such as the thirst level of consumers and their preference of beverage type. As mentioned earlier, we confirmed that none of the participants felt excessive thirst and none disliked green tea and Coke in the interview conducted before the measurement. Hence, we considered that the thirst level and beverage preference of the participants did not vary much, and this slight variation did not exert any serious influence on drinking satisfaction. However, in addition to evaluating the effect of the opening diameter, we also need to evaluate the effects of the material and shape of the bottle, the thirst level, and preference of beverage by uncertainty analysis (Worden et al., 2005; Du and Chen, 2000). Then, the evaluation function should be formulated by including the influential input factor to improve the accuracy of the function.

Appendix

Radial Basis Function Networks (RBFNs)

The RBFN (Orr, 1996) is a kind of neural network that yields a response surface by a superposition of basis functions. The output of the RBFN is given by the following equation:

$$O(\boldsymbol{x}) = \sum_{j=1}^{m} w_j h_j(\boldsymbol{x}) \tag{A.1}$$

where $\boldsymbol{x} = \{x_1, x_2, \cdots, x_n\}^T$ is a design variable vector, n is the number of design variables, w_j is the weight for $h_j(\boldsymbol{x})$, and m is the number of sampling points. $h_j(\boldsymbol{x})$ is an RBF given by

$$h_j(\boldsymbol{x}) = \exp\left(-\frac{\|\boldsymbol{x} - \boldsymbol{c}_j\|^2}{r_j^2} \right) \tag{A.2}$$

where $\boldsymbol{c}_j$ and r_j are the center and radius, respectively, of the j-th basis. In this study, we used $r_j = 1.0$ for design variables normalized in the range [0,1] (Arakawa et al., 2001). The learning of the RBFN involves obtaining appropriate weights for each basis and is identical to the minimization of energy of the RBFN. The energy of the RBFN is given by

$$E = \sum_{i=1}^{m} \{y_i - O(\boldsymbol{x}_i)\}^2 + \sum_{j=1}^{m} \lambda_j w_j^2 \tag{A.3}$$

where y_i is training data at the sampling point $\boldsymbol{x}_i = \{x_{i1}, x_{i2}, \cdots, x_{in}\}^T$ and λ_j is a regularization parameter whose value is 0.01 in this study. The optimal weight vector $\boldsymbol{w} = \{w_1, w_2, \cdots, w_m\}^T$ is given by the following equation:

$$\boldsymbol{w} = \left(\boldsymbol{H}^T \boldsymbol{H} + \boldsymbol{\Lambda}\right)^{-1} \boldsymbol{H}^T \boldsymbol{y} \tag{A.4}$$

where $\boldsymbol{H}$, $\boldsymbol{\Lambda}$, and $\boldsymbol{y}$ are given by

$$\boldsymbol{H} = \begin{bmatrix} h_1(x_1) & h_2(x_1) & \cdots & h_m(x_1) \\ h_1(x_2) & h_2(x_2) & \cdots & h_m(x_2) \\ \vdots & \vdots & \ddots & \vdots \\ h_1(x_p) & h_2(x_p) & \cdots & h_m(x_p) \end{bmatrix} \tag{A.5}$$

$$\boldsymbol{\Lambda} = \begin{bmatrix} \lambda_1 & 0 & 0 & 0 \\ 0 & \lambda_2 & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \lambda_m \end{bmatrix} \tag{A.6}$$

$$\boldsymbol{y} = \left(y_1, y_2, \cdots, y_p\right)^T \tag{A.7}$$

In this way, the main procedure of the learning results in calculating inverse matrix. Therefore, the learning of the RBFN can be terminated quickly, and additional learning can be calculated easily when new datasets are added.

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References

Arakawa, M., Nakayama, H., Ishikawa, H., 2001. Optimum design using radial basis function network and adaptive range genetic algorithms, 1st Report, Consideration in unconstrained optimization. Transactions of the Japan Society of Mechanical Engineering Series C. 67 (655), 789-796. (in Japanese)

Carus, D.A., Grant, C., Wattie, R., Pridham, M.S., 2006. Development and validation of a technique to measure and compare the opening characteristics of tamper-evident bottle closures. Packaging Technology and Science. 19 (2), 105-118.

Chihara, T., Yamazaki, K., Itoh, R., Han, J., 2009. Evaluation of drinking ease relative to the opening diameter and beverage type of aluminum beverage bottles. Journal of Food Engineering. 95(2), 264-271.

Du, X., Chen, W., 2000. Towards a better understanding of modeling feasibility robustness in engineering design. Transactions of the ASME, Journal of Mechanical Design. 122 (4), 385-394.

Fluent Incorporated, 2002. FIDAP User's Manual.

Han, J., Itoh, R., Nishiyama, S., Yamazaki, K., 2005. Application of structure optimization technique to aluminum beverage bottle design. Structural and Multidisciplinary Optimization. 29 (4), 304-311.

Huang, G.-Q., Huang, H.-X., 2007. Optimizing parison thickness for extrusion blow molding by hybrid method. Journal of Materials Processing Technology. 182 (1-3), 512-518.

Lewis, R., Menardi, C., Yoxall, A., Langley, J., 2007. Finger friction: grip and opening packaging. Wear. 263 (7-12), 1124-1132.

Masood, S.H., KeshavaMurthy, V., 2005. Development of collapsible PET water fountain bottles. Journal of Materials Processing Technology. 162-163, 83-89.

Miyaoka, Y., Miyaoka, S., Yamada, Y., 2000. The optimal volume for a swallow in healthy subjects. The Japanese Journal of Physiology. 50 (Supplement), 146.

Myers, R.H., Montgomery, D.C., 1995. Response surface methodology: process and product optimization using designed experiments. Wiley, New York.

Nagatani, M., Koga, H., Murayama, N., Igasaki, T., 2004, Analysis of swallowing using surface electromyography –influence on the kind and volume of ingested foods–. Technical Report of the Institute of Electronics, Information and Communication Engineering. 103 (637), 29-32. (in Japanese)

National Institute of Bioscience and Human-Technology, 1996. Human body dimensions data for ergonomic design. Japan Publication Service, Tokyo. (in Japanese)

Orr, M.J.L., 1996. Introduction to radial basis function networks. Available from http://anc.ed.ac.uk/rbf/rbf.html.

Thibault, F., Malo, A., Lanctot, B., Diraddo, R., 2007. Preform shape and operating condition optimization for the stretch blow molding process. Polymer Engineering and Science. 47 (3), 289-301.

Worden, K., Manson, G., Lord, T.M., Friswell, M.I., 2005. Some observations on uncertainty propagation through a simple nonlinear system. Journal of Sound and Vibration. 288 (3), 601-621.

Yamazaki, K., Chihara, T., Itoh, R., Han, J., Nishiyama, S., 2007. Evaluation method of drinking ease for aluminum beverage bottles. In: Proceedings of the ASME 2007 International Design Engineering Technical Conferences & Design Automation Conference, Paper No. 35637, Las Vegas, CD-ROM.

Yamazaki, K., Itoh, R., Watanabe, M., Han, J., Nishiyama, S., 2007. Applications of structural optimization techniques in light weighting of aluminum beverage can ends. Journal of Food Engineering. 81 (2), 341-346.

Yoxall, A., Janson, R., 2007. Fact or friction: a model for understanding the openability of wide mouth closures. Packaging Technology and Science. 21 (3), 137-147.

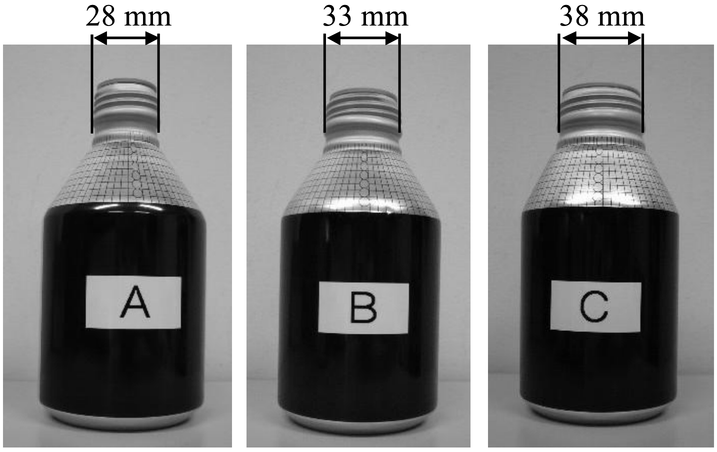
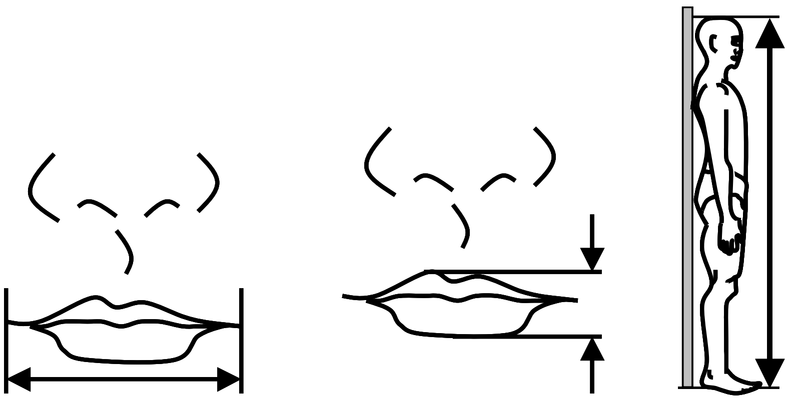


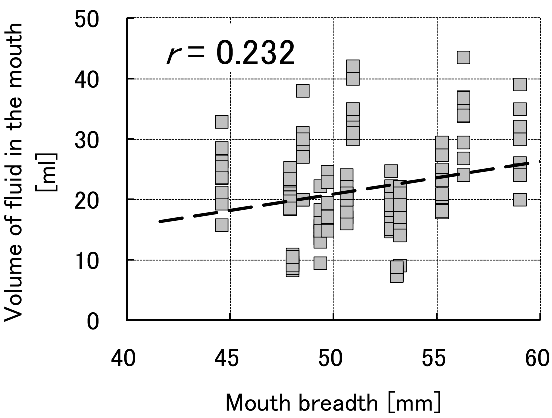
Fig. 1. Test bottles

Fig. 2. Drinking test

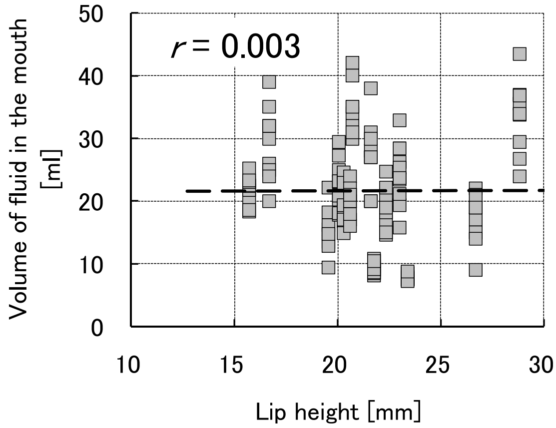


(a) Mouth breadth (b) Lip height (c) Body height

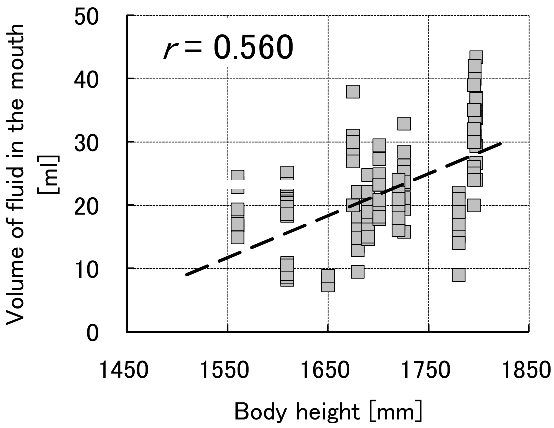
Fig. 3. Measured dimensions of participants



(a) Mouth breadth



(b) Lip height



(c) Body height

Fig. 4. Relationship between volume of fluid in the mouth and dimensions of human body

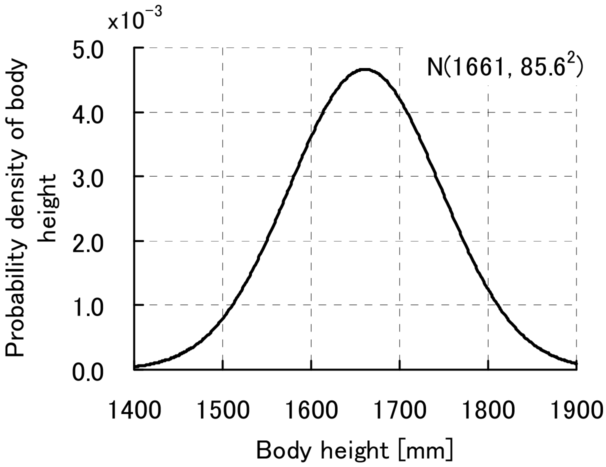


Fig. 5. Distribution of body height

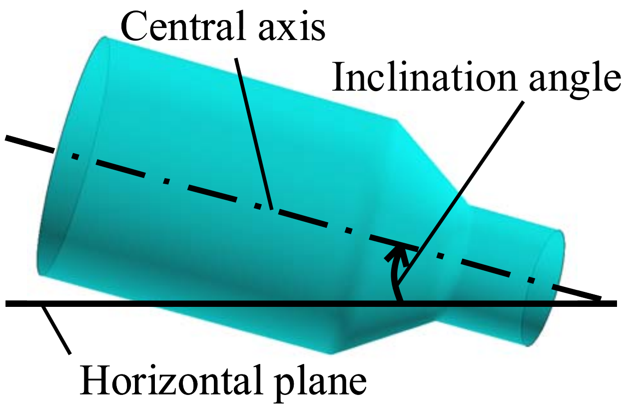


Fig. 6. Definition of inclination angle

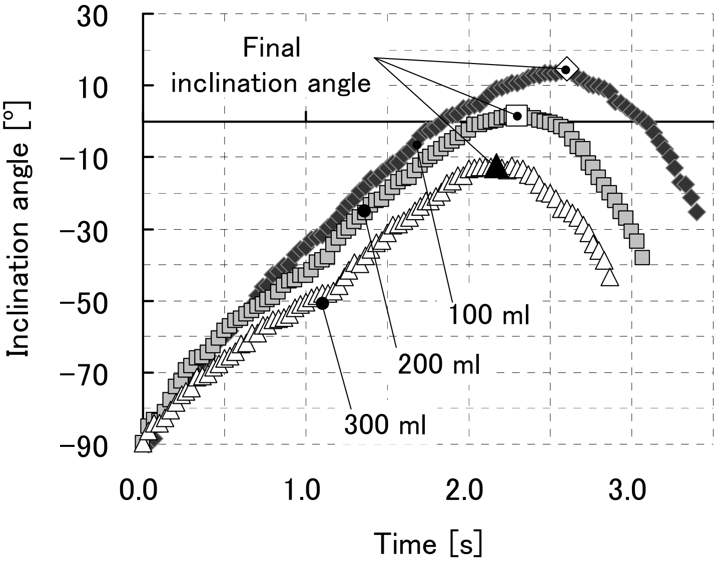


Fig. 7. History plots of inclination angle

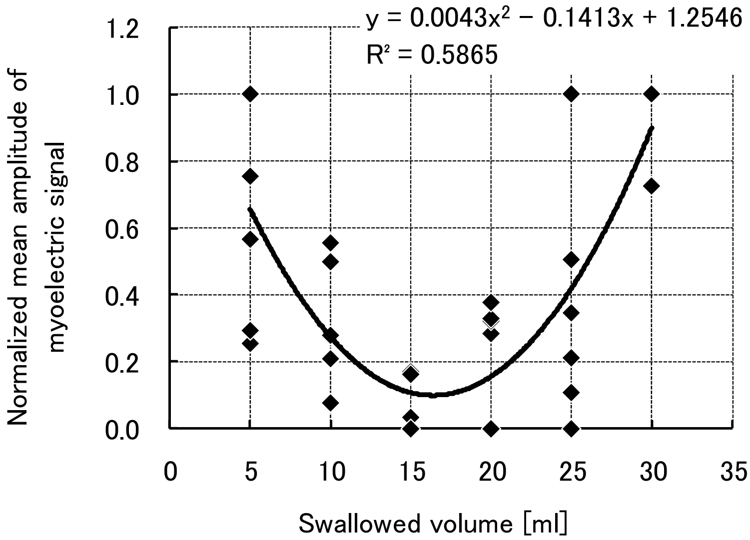


Fig. 8. Relationship between swallowed volume and normalized mean amplitude of myoelectric signal

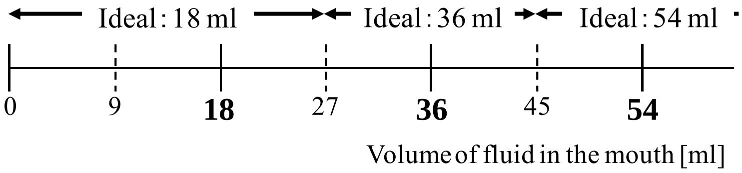


Fig. 9. Definition of ideal volume of fluid in the mouth

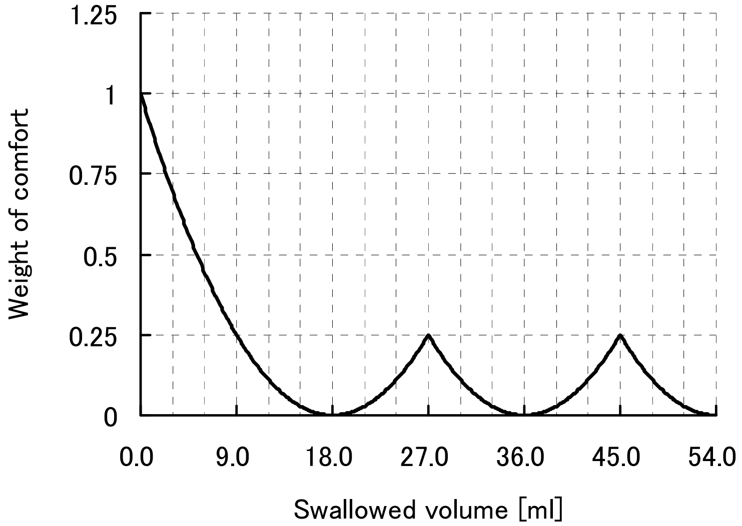


Fig. 10. Weight function of comfort

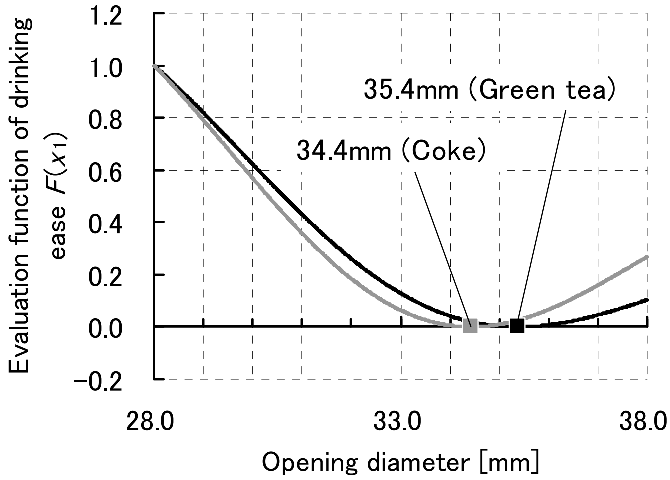
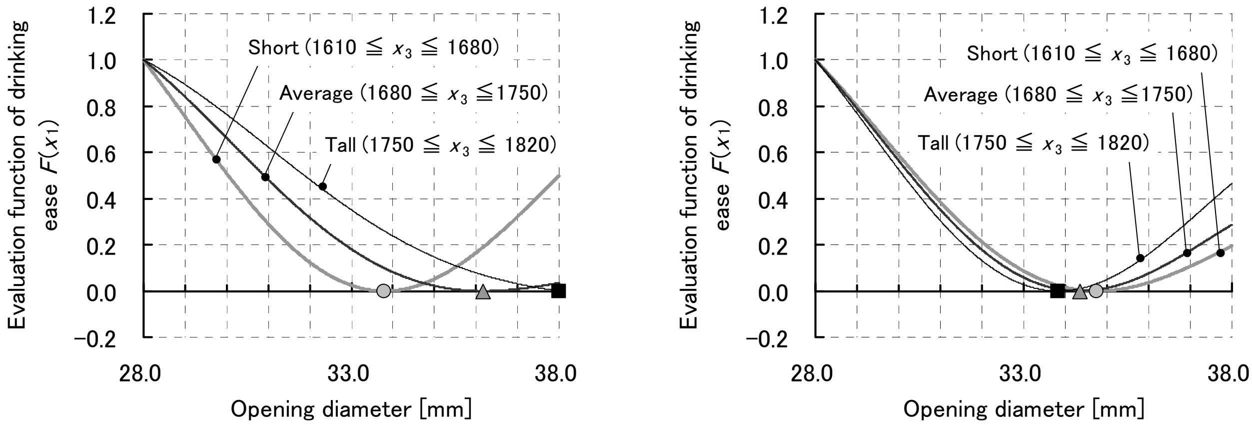


Fig. 11. Evaluation function of drinking ease



(a) Green tea (b) Coke

Fig. 12. Comparison between evaluation functions for different ranges of heights in the case of (a) green tea and (b) Coke

Table 1 Sampling points

Sampling point	x_1 [mm]	x_2 [ml]	x_4 [°]	x_5 [s]
1	28.0	100	5.0	1.70
2	28.0	200	–10.0	3.35
3	28.0	300	–25.0	5.00
4	28.0	200	2.5	1.70
5	28.0	300	–12.5	3.35
6	28.0	100	17.5	5.00
7	28.0	300	0.0	1.70
8	28.0	100	30.0	3.35
9	28.0	200	15.0	5.00
10	33.0	200	–10.0	1.70
11	33.0	300	–25.0	3.35
12	33.0	100	5.0	5.00
13	33.0	300	–12.5	1.70
14	33.0	100	17.5	3.35
15	33.0	200	2.5	5.00
16	33.0	100	30.0	1.70
17	33.0	200	15.0	3.35
18	33.0	300	0.0	5.00
19	38.0	300	–25.0	1.70
20	38.0	100	5.0	3.35
21	38.0	200	–10.0	5.00
22	38.0	100	17.5	1.70
23	38.0	200	2.5	3.35
24	38.0	300	–12.5	5.00
25	38.0	200	15.0	1.70
26	38.0	300	0.0	3.35
27	38.0	100	30.0	5.00

Table 2 Ranking results of drinking ease

Sample	Number of participants			Scores
	1st	2nd	3rd	
Green tea				
28 mm opening	0	3	33	39
33 mm opening	17	18	1	88
38 mm opening	19	15	2	89
Coke				
28 mm opening	1	9	26	47
33 mm opening	25	10	1	96
38 mm opening	10	17	9	73

Table 3 Optimum opening diameter for each range of height and beverage type

Beverage type	Optimum opening diameter [mm]		
	Short	Average	Tall
Green tea	33.8	36.2	38.0
Coke	34.8	34.3	33.8