

Evaluation function of drinking ease from aluminum beverage bottles relative to optimum bottle opening diameter and beverage type

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

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4 Running title: Evaluation Function of Drinking Ease

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14 **Abstract**

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

34
35 **Keywords:** Ergonomics, Drinking ease, Optimization, Aluminum beverage bottle

36
37 **1. Introduction**

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

50 Aluminum beverage bottles having screw tops with diameters of 28 mm and 38 mm were launched in the Japanese
51 market in 2000 in keeping with the modern-day drinking habits of consumers; therefore, consumers are now familiar
52 with bottles of these dimensions. Usually, consumers drink beverages in one of several ways: directly from the bottle
53 opening, using a straw, or from a glass. Because aluminum beverage bottles can be resealed, consumers often carry

54 them outdoors and drink directly from the bottle opening. It is, therefore, important for manufacturers of aluminum
55 beverage bottles to design bottles after thoroughly considering the satisfaction levels of consumers drinking directly
56 from the bottle opening. However, these dimensions were not designed on the basis of drinking satisfaction. To ensure
57 survival in a competitive market, of course, it is important for manufacturers of aluminum beverage bottles to improve
58 the usability of a part that is used without difficulty such as drinking satisfaction in addition to that of awkward part.
59 Therefore, it is essential to develop a method for evaluating consumer feelings while they are drinking a beverage
60 directly from the bottle opening and then determine the optimum opening diameter size for ensuring consumers'
61 drinking satisfaction.

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

82 Structure optimization techniques based on finite element analysis (FEA) have been employed for the development
83 of two-piece aluminum beverage cans and bottles with the aim of achieving better performance under various loading
84 conditions. For instance, the lid can be made lightweight to prevent the bottle from being damaged by buckling and to
85 maximize the strength of the bottle bottom against axial loads and internal pressure (Yamazaki et al., 2007; Han et al.,
86 2005). In addition, such techniques have also been applied to develop PET bottles to make them lightweight and
87 collapsible under a normal load by a human subject to the constraint of the buckling strength (Masood and
88 KeshavaMurthy, 2005). Further, the shape optimization method has been applied to the prediction of optimal preform
89 geometry or parison thickness distribution of plastic bottles in order to ensure their conformance to the required
90 thickness distribution (Thibault et al., 2007; G.-Q. Huang and H.-X. Huang, 2007). However, these researches
91 formulated and optimized only the mechanical function of beverage containers and not the evaluation function of
92 consumer satisfaction.

93 Design methods for determining consumers' satisfaction, for example, drinking ease, and for maximizing their

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

103

104 **2. Evaluation Function of Drinking Ease**

105 **2.1 Definition of evaluation function of drinking ease**

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

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

119 **2.2 Selection of design and state variables**

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

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

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

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

141 2.3 Formulation of evaluation function of drinking ease

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

147

$$148 \quad F(x_1) = \int_{x_{2\min}}^{x_{2\max}} \int_{x_{3\min}}^{x_{3\max}} \{O(x_1, x_2, x_3) \cdot P(x_3)\} dx_3 dx_2 \quad (1)$$

149

150 where x_1 , x_2 , and x_3 denote the bottle opening diameter, volume of remaining beverage, and body height, respectively.
151 $x_{2\min}$ 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
152 minimum and maximum bounds of the body height, respectively. $P(x_3)$ is a weight function based on the distribution of
153 height. From a statistical data (National Institute of Bioscience and Human-Technology, 1966), the distribution of height
154 on Japanese subjects is shown in Fig. 5, if it follows a normal distribution. We apply the distribution of height as a
155 weight function.

156 $O(x_1, x_2, x_3)$ is the response surface of the output predicted using the RBFN, which is one of the response surface
157 methods. The detailed procedure for constructing a response surface using the RBFN is provided in the Appendix.
158 Response surface methods approximate functional spaces globally by using m pairs of the input vector and output value
159 (\mathbf{x}_p, y_p) ($p = 1, 2, \dots, m$), where $\mathbf{x}_p = (x_{p1}, x_{p2}, \dots, x_{pm})$ is the input vector and y_p is the output value. The response surface is
160 written as follows:

161

$$162 \quad \hat{y} = \sum_{p=1}^m w_p \phi_p(\mathbf{x}_p) \quad (2)$$

163

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

170 2.4 Consideration of flow rate adjustability

171 The volume of fluid in the mouth probably changes with a change in the drinking actions of consumers. In order to

172 account for the variability of the volume of fluid in the mouth while deriving the evaluation function, we define the
 173 input values of the training data of the RBFN as follows:

174

$$175 \quad y_{ijk} = \int_{x_{4\min,k}}^{x_{4\max,k}} \int_{x_{5\min}}^{x_{5\max}} \{w(V_{ijk}) \cdot P_{x_4,ijk}(x_4) \cdot P_{x_5,ijk}(x_5)\} dx_5 dx_4 \quad (3)$$

176

177 where y_{ijk} denotes the integrated difference between the volume of fluid in the mouth in consideration of its variation
 178 and the ideal volume over the entire range of drinking actions. In addition, i , j , and k denote the i -th participant, j -th
 179 opening diameter, and k -th volume of remaining beverage, respectively; x_4 denotes the final inclination angle of the
 180 bottle when a participant drinks the beverage; and x_5 is the time duration in which the inclination angle of the bottle
 181 changes from the initial angle to the final angle. As shown in Fig. 6, we define the inclination angle of the bottle as the
 182 acute angle between the horizontal plane and the central axis of the bottle. In order to determine representative variables
 183 of the drinking actions of consumers, we recorded the drinking actions of several participants with a video recorder and
 184 measured the inclination angle of the bottle. In this experiment, we used bottles with an opening diameter of 33 mm; its
 185 maximum capacity was 300 ml, and it was filled with 100 ml, 200 ml, and 300 ml of the beverage. Fig. 7 shows an
 186 example of the history plots of the inclination angle. Fig. 7 and the results of the other participants show that the
 187 rotation velocities of the bottles are almost constant when they drink beverages directly from the bottle opening.
 188 Therefore, for simplicity, we assume that the rotation velocity of the bottle is constant and use the final inclination angle
 189 and the abovementioned time duration as representative variables of the drinking actions of participants. $x_{4\min,k}$ and
 190 $x_{4\max,k}$ in Eq. (3) denote the minimum and maximum values, respectively, of the final inclination angle. Similarly, $x_{5\min}$
 191 and $x_{5\max}$ denote the minimum and maximum values, respectively, of the time duration. We set different final
 192 inclination angles corresponding to each volume of remaining beverage, because the final inclination angle depends on
 193 this volume.

194 In Eq. (3), $w(V_{ijk})$ denotes the weight function of comfort, which will be described in detail in the next subsection;
 195 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
 196 volume of fluid in the mouth in consideration of its variation, is given as follows:

197

$$198 \quad V_{ijk} = \bar{V}_{ijk} + \Delta V_{ijk}(x_4, x_5) \quad (4)$$

199

200 where \bar{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
 201 the mouth because of the uncertainty of the drinking actions, and it is given by the following equation:

202

$$203 \quad \Delta V_{ijk}(x_4, x_5) = Q(x_1, x_2, x_4, x_5) - Q(x_1, x_2, \bar{x}_{4,ijk}, \bar{x}_{5,ijk}) \quad (5)$$

204

205 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
 206 subsection, we describe how to approximate $Q(x_1, x_2, x_4, x_5)$. $\bar{x}_{4,ijk}$ and $\bar{x}_{5,ijk}$ are the average values of the final
 207 inclination angle and time duration, respectively. Therefore, Eq. (4) expresses the volume of fluid in the mouth in
 208 consideration of its variation owing to the uncertainty of drinking actions.

209 Let $P_{x_4,ijk}(x_4)$ and $P_{x_5,ijk}(x_5)$ denote the probability density functions of the final inclination angle and time

210 duration, respectively, obtained by the assumption that the drinking actions follow a normal distribution; they are given
 211 by

$$213 \quad P_{x_4,ijk}(x_4) = \frac{1}{\sqrt{2\pi}\sigma_{x_4,ijk}} \exp\left\{-\frac{(x_4 - \bar{x}_{4,ijk})^2}{2\sigma_{x_4,ijk}^2}\right\} \quad (6)$$

$$215 \quad P_{x_5,ijk}(x_5) = \frac{1}{\sqrt{2\pi}\sigma_{x_5,ijk}} \exp\left\{-\frac{(x_5 - \bar{x}_{5,ijk})^2}{2\sigma_{x_5,ijk}^2}\right\} \quad (7)$$

216
 217 where $\sigma_{x_4,ijk}$ and $\sigma_{x_5,ijk}$ are the standard deviations of the final inclination angle and time duration, respectively.

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

220 **2.5 Approximation of weight function of comfort**

221 We performed an experiment to determine the ideal fluid volume for a single swallow and subsequently determine
 222 the expected ideal volume of fluid in the mouth and approximate $w(V_{ijk})$. The participants in the experiment were six
 223 university students (three males and females each). We measured the myoelectric potentials of participants' throats
 224 (sternohyoid muscle) when they swallowed water. This muscle is involved in the action of swallowing (Nagatani, 2004).
 225 The myoelectric potentials were measured, at a sampling frequency of 1000 Hz, by attaching surface electrodes
 226 (DE-2.1, DELSYS Inc.) to the measurement positions; the measured potentials were then stored in a computerized
 227 record after amplification (Bagnoli-2, DELSYS Inc. and UAS-108S, UNIQUE MEDICAL Co., Ltd.). The participants
 228 were required to drink water in a single swallow, and the volume of water was increased in 5-ml increments from 5 to
 229 30 ml. The measurement was performed two times for each volume. The measured myoelectric potentials were
 230 integrated from the beginning to end of muscle contraction. The integrated myoelectric potentials were divided by the
 231 time elapsed from the beginning to the end of muscle contraction (hereafter referred to as "mean amplitude of the
 232 myoelectric signal").

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

$$236 \quad \bar{M}_i = \frac{M_i - M_{\min,i}}{M_{\max,i} - M_{\min,i}} \quad (8)$$

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

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

$$251 \quad w(V_{ijk}) = \frac{1}{18^2} (V_{ijk} - V_{ideal})^2 \quad (9)$$

252
 253 Here, V_{ideal} denotes the ideal volume of fluid in the mouth. Initially, the weight function of comfort, $w(V_{ijk})$, reaches a
 254 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
 255 mouth increases, consumers probably swallow in plural divided the fluid, because it is hard to swallow a large volume
 256 of beverage at once. Therefore, if the volume of fluid in the mouth becomes relatively large, $w(V_{ijk})$ should be calculated
 257 for each divided volume of fluid for a single swallow. However, it is difficult to measure or determine the divided
 258 volume of fluid for a single swallow when consumers swallow in plural divided the volume of fluid in the mouth.
 259 Hence, we adjust $w(V_{ijk})$ as a function that reaches a minimum at multiples of 18 ml under the assumption that the ideal
 260 volume of fluid for a single swallow is 18 ml and continues at the intermediate between multiples of 18 ml (see Fig.
 261 10).
 262

263 The ideal volume of fluid for a single swallow may not be a unique value; it may vary with anthropometric
 264 dimensions such as body height. In addition, the ideal volume of fluid for a single swallow is affected by the style of
 265 drinking, such as drinking in one gulp and sipping. However, it is difficult to assemble a large number of participants
 266 for the experiments and to determine an optimum volume; furthermore, it is difficult to classify and specify the drinking
 267 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
 268 ideal volume of fluid for a single swallow. In addition, in the measurement of volume of fluid in the mouth, which is
 269 shown in section 3.1, we just asked the participants to drink one mouthful of beverage and did not give them any other
 270 instructions on how to drink.

271 **2.6 Approximation of fluid volume function**

272 We used the response surface methodology based on design of experiments (DOE) (Myers and Montgomery, 1995)
 273 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
 274 remaining beverage, final inclination angle, and time duration, by using an orthogonal array of the DOE. Then, we
 275 performed 3D fluid dynamics simulations at sampling points based on the orthogonal array by using the analysis code
 276 FIDAP (Fluent Inc.), under the same analysis conditions as those in our previous study (Chihara et al., 2009).

277 First, we carried out a factorial analysis in which each variable has two levels, on the basis of the measurement
 278 result of participants' drinking actions, so as to investigate the interaction among four variables—the bottle opening size
 279 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
 280 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
 281 x_5 —had statistically significant differences; thus, the four variables were assigned to the L_{27} orthogonal array of the
 282 DOE, so that these three combinations would be considered. In addition, we found that the final inclination angle was

283 dependent on the volume of remaining beverage; hence, we set the levels of the final inclination angle as follows:

284

285 Lower limit of x_4 : (Intermediate value of x_4) $- 12.5^\circ$

286 Intermediate value of x_4 : $((-3x_2/20) + (65/2))^\circ$

287 Upper limit of x_4 : (Intermediate value of x_4) $+ 12.5^\circ$

288

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

290

$$28.0 \leq x_1 \leq 38.0$$

291

$$100 \leq x_2 \leq 300$$

(10)

$$1.70 \leq x_3 \leq 5.00$$

292

293 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
294 response surface methodology. Further, the response surface was approximated using a quadratic polynomial that
295 includes cross terms, as follows:

296

$$\begin{aligned} Q(x_1, x_2, x_4, x_5) = & -1.27 \times 10^2 + 1.12x_1 - 3.79 \times 10^{-2} (x_1 - 3.30 \times 10^1)^2 \\ & + 4.25 \times 10^{-1} x_2 - 2.98 \times 10^{-4} (x_2 - 2.0 \times 10^2)^2 + 2.73x_4 + 7.70 \times 10^{-2} (x_4 + 1.50 \times 10^{-1} x_2 - 3.25 \times 10^1)^2 \\ & + 7.97x_5 - 1.50(x_5 - 3.35)^2 + 7.13 \times 10^{-2} (x_1 - 3.30 \times 10^1)(x_4 + 1.50 \times 10^{-1} x_2 - 3.25 \times 10^1) \\ & - 1.31 \times 10^{-1} (x_1 - 3.30 \times 10^1)(x_5 - 3.35) + 6.18 \times 10^{-1} (x_4 + 1.50 \times 10^{-1} x_2 - 3.25 \times 10^1)(x_5 - 3.35) \end{aligned} \quad (11)$$

298

299 3. Results of optimization and discussion

300 3.1 Measurement of volume of fluid in the mouth and recording of drinking actions

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

311 3.2 Results of optimization

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

315

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

317

318 Fig. 11 shows the evaluation functions of drinking ease for green tea and Coke. Table 2 lists the ranking results for
319 green tea and Coke, as submitted by all participants. In all, 36 rankings were collected (12 participants \times 3 volumes of
320 remaining beverage). With 3 points given to the first rank, 2 points to the second, and 1 to the third rank, the total
321 ranking scores of the three kinds of bottles were calculated as shown in the last column of Table 2. Fig. 11 shows that
322 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
323 $x_1 = 34.4$ mm. The optimum opening diameter for Coke is smaller than that for green tea; however, the difference is
324 only about 1 mm.

325 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
326 same, whereas in the case of coke, the 33 mm opening shows the highest score and the 38 mm opening has the second
327 highest score. The values of the evaluation function in the case of green tea, shown in Fig. 11, are almost the same at 33
328 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
329 qualitative trend of evaluation function agrees with the participants' subjective satisfaction.

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

337 3.3 Discussion

338 We consider that the evaluation function formulated in Eq. (1) is valid for expressing the drinking satisfaction,
339 because its qualitative trend agrees with the participants' subjective satisfaction. Result of the optimization of the
340 evaluation function of drinking ease and the fluid volume from openings with a diameter of 35.4 mm (in the case of
341 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
342 mouth; participants reported ease of drinking at these diameters in the ranges mentioned in Eq. (12). In addition, the
343 preferred opening diameter for Coke is smaller than that for green tea. This may be explained by the fact that
344 carbonated beverages have a foaming tendency, and when the opening diameter is relatively small, the fluid volume is
345 small, thereby making it easy for the drinker to adjust the flow and thus feel comfortable. This is in agreement with the
346 result of our previous study that the factor of flow rate adjustability is more significant than the volume of fluid in the
347 mouth in the case of carbonated beverages. However, the difference in the optimum opening diameters for green tea and
348 Coke was only about 1 mm; hence, it was observed that the beverage type did not strongly affect the optimum opening
349 diameter in the case of these participants.

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

354 tea, they prefer a larger opening diameter that permits a larger volume of beverage to flow into the mouth.

355 From a comparison between evaluation functions for different ranges of heights, it is obvious that the drinking
356 satisfaction is worse in the case of a relatively small opening diameter irrespective of the beverage type and participant
357 height. On the other hand, in the case of green tea, the relatively large opening diameter does cause the drinking
358 satisfaction to worsen for the “short” range participants. Thus, the drinking satisfaction is not very low irrespective of
359 the beverage type and height of participants around the neighborhood of the optimum opening diameters (approximately
360 34 to 36 mm). Therefore, we conclude that perhaps the optimum diameter, which is obtained by optimizing the
361 evaluation function, is a robust solution for beverage type and the height of the participants.

362

363 **4. Conclusions**

364 In this study, we have proposed an evaluation function of drinking ease, which considers the volume of beverage
365 flowing into the drinker’s mouth and flow rate adjustability, for determining the optimum opening diameter for drinking
366 ease. We have also optimized the evaluation function by performing experiments and found that the volume of beverage
367 consumed by the participants is closest to the ideal volume of fluid in the mouth and their comfort level is highest when
368 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
369 the optimum opening diameters are only for these participants. Both these optimal opening diameters are around 33 mm,
370 which is in agreement with the result of our previous study that the opening diameter of 33 mm is best suited for Japan’s
371 young adult consumers irrespective of the beverage type. Thus, these optimum opening diameters appear to be accurate,
372 and we believe that the proposed evaluation function may provide quantitative information on drinking ease, which is
373 actually a qualitative feeling. Thus, we have used the proposed function to determine the optimum bottle opening
374 diameter from which consumers can comfortably drink an optimum volume of beverage (i.e., drinking ease). Moreover,
375 results of optimization of the evaluation function have shown that the optimal opening diameter for drinking ease
376 depends on the beverage type. Therefore, manufacturers of aluminum beverage bottles should design the dimensions of
377 bottle openings by considering the beverage type, thus ensuring the comfort and satisfaction of consumers. We have
378 also found that the optimal opening diameter depends on individual differences, e.g., the height of consumers. Thus, the
379 proposed evaluation function can be used to determine the optimum opening diameter of bottles that are to contain
380 beverages targeted at a particular category of consumers.

381 Although we had intended to include participants of all age groups in this study, only young students readily
382 consented to participate because it was easy to ask them to be the participants. However, for designing a bottle opening
383 from which consumers of all age groups and genders achieve drinking satisfaction, it is essential to consider a broad
384 range of ages of participants of the study; in particular, children should participate in such a study. If, as concluded in
385 the study, body height is one of determining factors for the optimum opening diameter, the diameter for children
386 probably varies much more than that for adults. Perhaps the optimum opening diameter for the drinking satisfaction of
387 children will be smaller than that for adults. Drinking satisfaction is affected by the following design variables: opening
388 diameter and the material and shape of the bottle. Across the range of bottles presently available in the market, the
389 material and shape hardly differ, because of the ease of recycling and the forming process of the current material and.
390 Therefore, we focus on the effect of the cap diameter, which is relatively easy to change, on drinking satisfaction. In
391 addition, perhaps the drinking satisfaction is affected by factors such as the thirst level of consumers and their
392 preference of beverage type. As mentioned earlier, we confirmed that none of the participants felt excessive thirst and
393 none disliked green tea and Coke in the interview conducted before the measurement. Hence, we considered that the

394 thirst level and beverage preference of the participants did not vary much, and this slight variation did not exert any
 395 serious influence on drinking satisfaction. However, in addition to evaluating the effect of the opening diameter, we also
 396 need to evaluate the effects of the material and shape of the bottle, the thirst level, and preference of beverage by
 397 uncertainty analysis (Worden et al., 2005; Du and Chen, 2000). Then, the evaluation function should be formulated by
 398 including the influential input factor to improve the accuracy of the function.

399

400 **Appendix**

401 **Radial Basis Function Networks (RBFNs)**

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

404

$$405 \quad O(\mathbf{x}) = \sum_{j=1}^m w_j h_j(\mathbf{x}) \quad (\text{A.1})$$

406

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

409

$$410 \quad h_j(\mathbf{x}) = \exp\left(-\frac{\|\mathbf{x} - \mathbf{c}_j\|^2}{r_j^2}\right) \quad (\text{A.2})$$

411

412 where \mathbf{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
 413 variables normalized in the range [0,1] (Arakawa et al., 2001). The learning of the RBFN involves obtaining appropriate
 414 weights for each basis and is identical to the minimization of energy of the RBFN. The energy of the RBFN is given by

415

$$416 \quad E = \sum_{i=1}^m \{y_i - O(\mathbf{x}_i)\}^2 + \sum_{j=1}^m \lambda_j w_j^2 \quad (\text{A.3})$$

417

418 where y_i is training data at the sampling point $\mathbf{x}_i = \{x_{i1}, x_{i2}, \dots, x_{in}\}^T$ and λ_j is a regularization parameter whose value is
 419 0.01 in this study. The optimal weight vector $\mathbf{w} = \{w_1, w_2, \dots, w_m\}^T$ is given by the following equation:

420

$$\mathbf{w} = (\mathbf{H}^T \mathbf{H} + \mathbf{A})^{-1} \mathbf{H}^T \mathbf{y} \quad (\text{A.4})$$

421

where \mathbf{H} , \mathbf{A} , and \mathbf{y} are given by

422

$$\mathbf{H} = \begin{bmatrix} h_1(x_1) & h_2(x_1) & \dots & h_m(x_1) \\ h_1(x_2) & h_2(x_2) & \dots & h_m(x_2) \\ \vdots & \vdots & \ddots & \vdots \\ h_1(x_p) & h_2(x_p) & \dots & h_m(x_p) \end{bmatrix} \quad (\text{A.5})$$

423

424
$$\mathbf{A} = \begin{bmatrix} \lambda_1 & 0 & 0 & 0 \\ 0 & \lambda_2 & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \lambda_m \end{bmatrix} \quad (\text{A.6})$$

425
426
$$\mathbf{y} = (y_1, y_2, \dots, y_p)^T \quad (\text{A.7})$$

427
428 In this way, the main procedure of the learning results in calculating inverse matrix. Therefore, the learning of the
429 RBFN can be terminated quickly, and additional learning can be calculated easily when new datasets are added.

430
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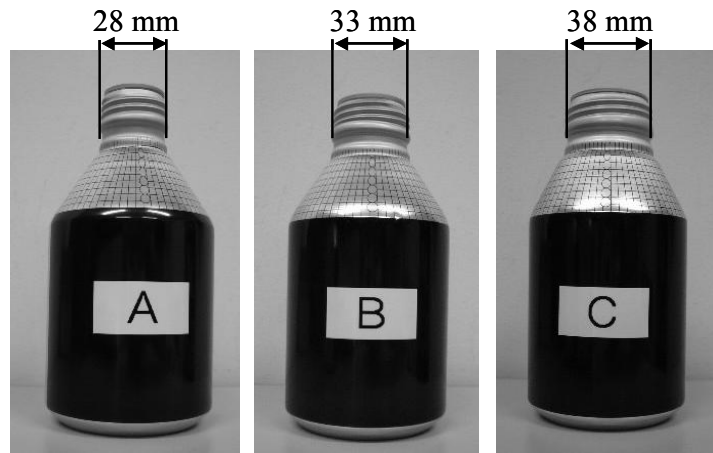


Fig. 1. Test bottles

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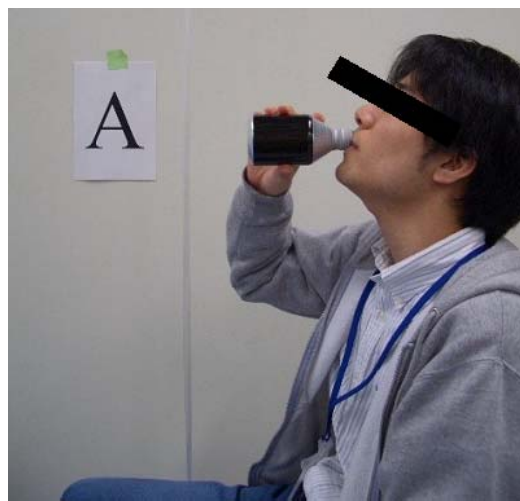
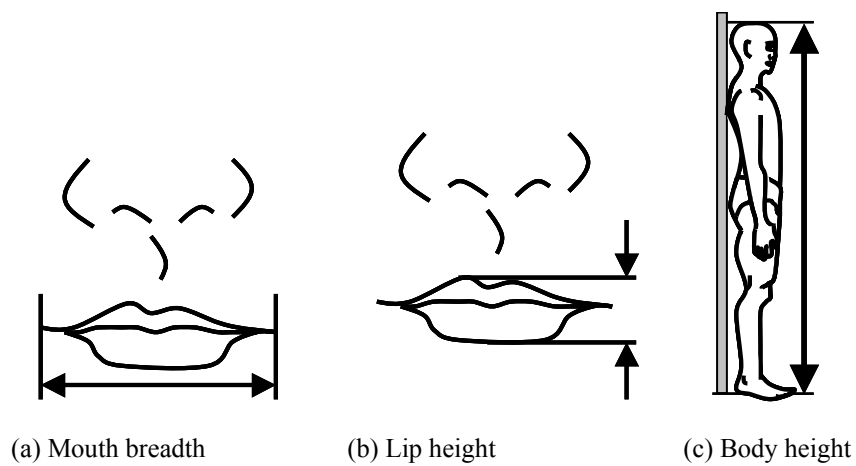


Fig. 2. Drinking test

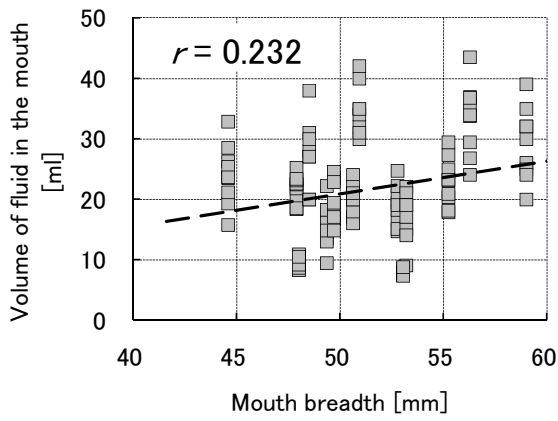
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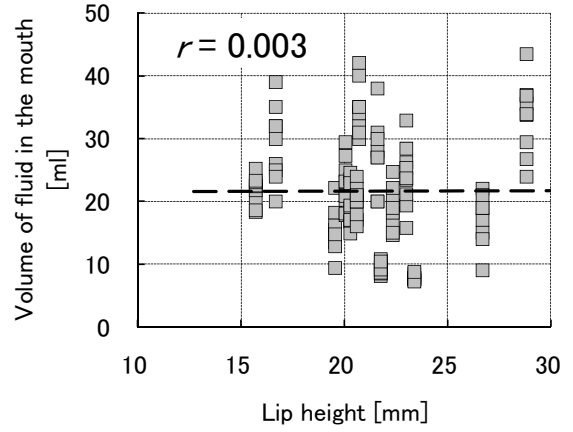
(a) Mouth breadth (b) Lip height (c) Body height

Fig. 3. Measured dimensions of participants

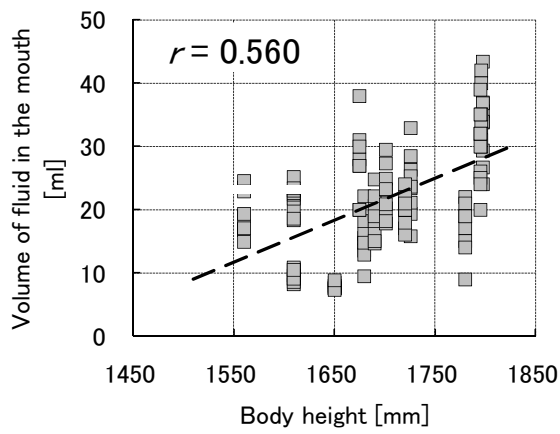
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(a) Mouth breadth



(b) Lip height



(c) Body height

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

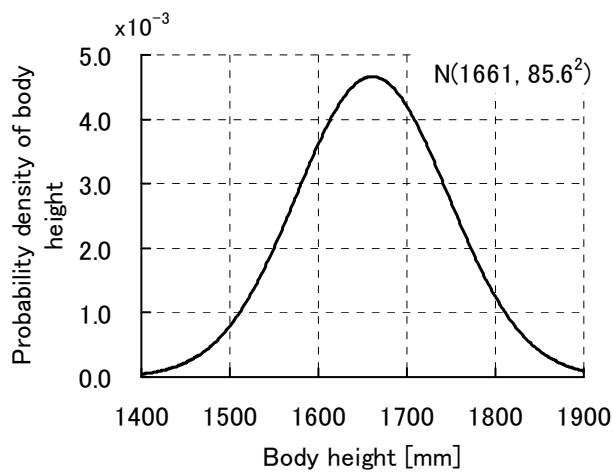


Fig. 5. Distribution of body height

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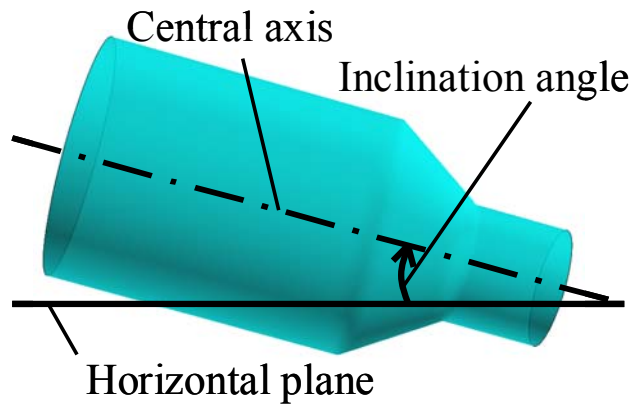


Fig. 6. Definition of inclination angle

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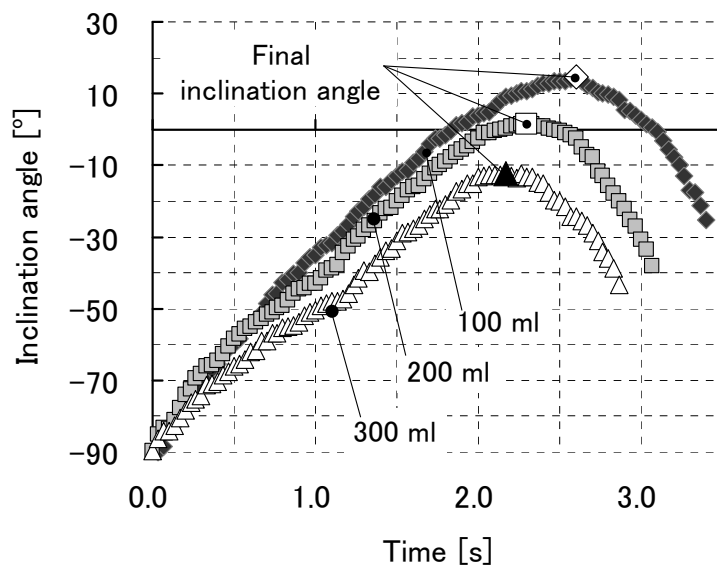


Fig. 7. History plots of inclination angle

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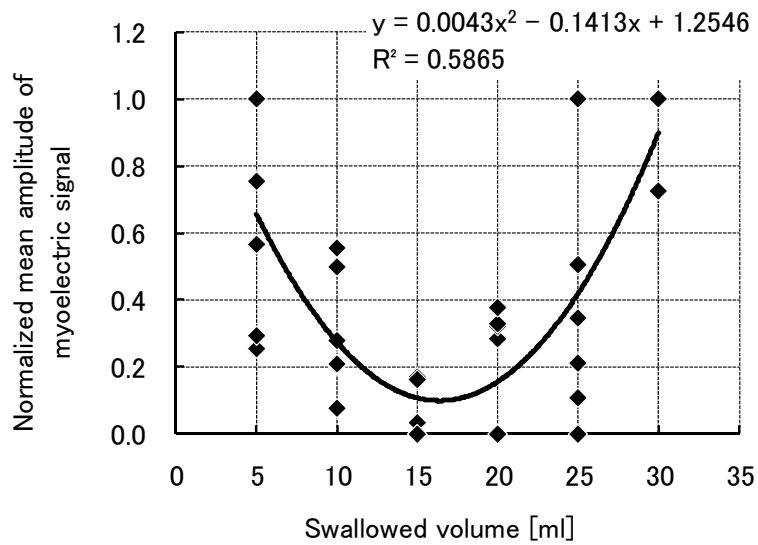


Fig. 8. Relationship between swallowed volume and normalized mean amplitude of myoelectric signal

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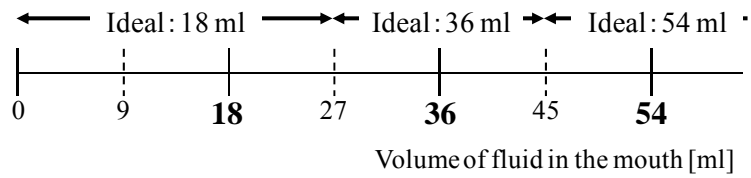


Fig. 9. Definition of ideal volume of fluid in the mouth

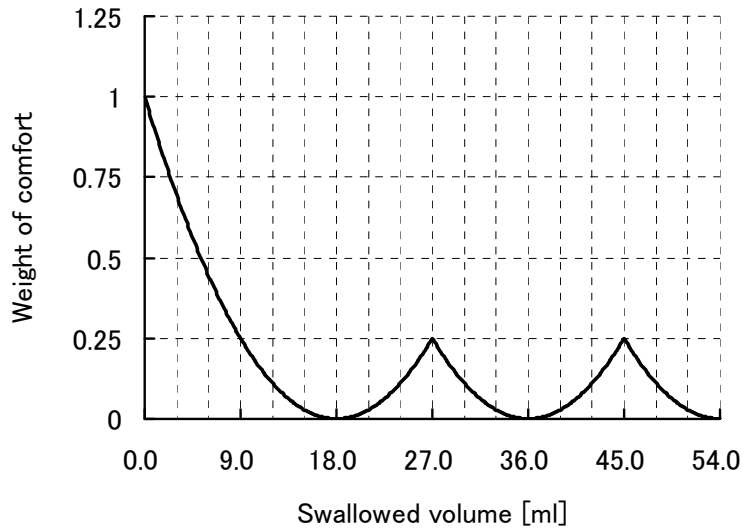


Fig. 10. Weight function of comfort

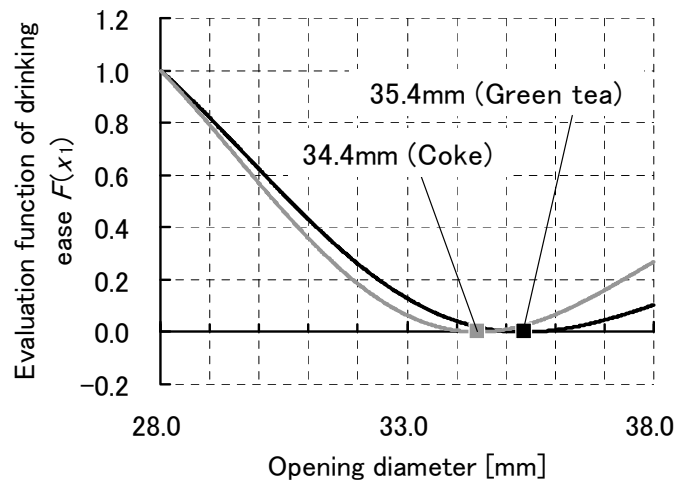
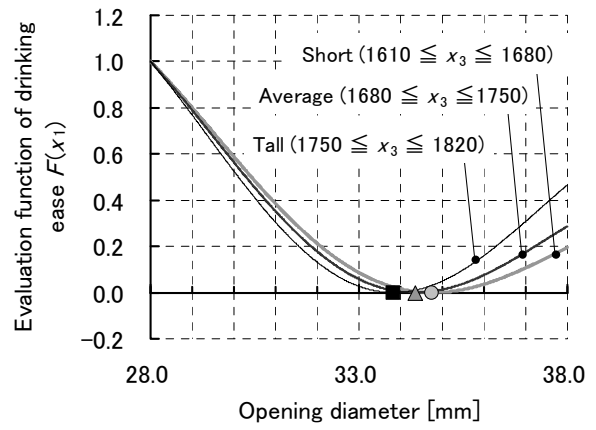
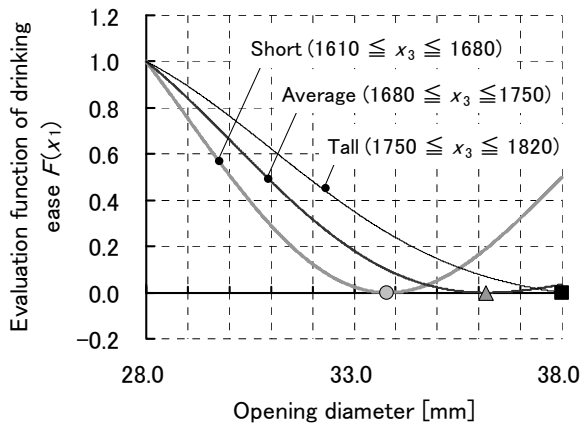


Fig. 11. Evaluation function of drinking ease

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(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

537

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

538

539

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

540

541

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

542