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Optimal design of a haptic popping toy using response surface

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Abstract
Mechanical buckling of a switch or button produces an attractive sensation of touch; however, a method to optimize the haptic pleasantness caused by buckling has not been established and well demonstrated. In this study, we optimized a popping elastic dome toy that provides pleasant haptic sensations when pushed or buckled. Toys with different physical parameters were manufactured following the Box-Behnken design, and their comfort was evaluated by the users. The design parameters that maximize haptic pleasantness were determined using the response surface method. The optimally designed popping toy was equally as comfortable as the best one in the initial specimen set. Further, haptic pleasantness was found to be largely determined by the ease of pushing and haptic feel at the moment of buckling. This approach is expected to improve the haptic sensations of various commercial products such as mechanical switches.

Keywords : Response surface, Buckling, Pleasantness, Stiffness, Prototyping

1. Introduction

Humans unconsciously touch many objects and materials in their daily lives (Nagano et al., 2013, 2014; Peck and Childers, 2003, 2006; Ujitoko, 2023), and this may partially be because we find tactile experience entertaining. Certain toys, such as the haptic popping toy shown in Fig. 1, stimulate such psychological aspects. The toy creates an engaging tactile experience by utilizing the rapid change in the reaction force when the rubber hemispherical dome is pressed and buckled by a fingertip. In addition to toys, mechanical switches or buttons, such as those used inside automobiles and keyboards, are associated with haptic sensations that affect user satisfaction (Gaspar et al., 2017; Hatzfeld et al., 2010; Kim and Lee, 2013; Li et al., 2013; Schütte and Eklund, 2005; Simon and Jörgen, 2005; Stamer et al., 2020; Vieira et al., 2017; Wellings et al., 2010; Zheng et al., 2022). Singular patterns of reaction forces and sounds (Burnett and Irune, 2009; Miyari et al., 2022) caused by the buckling or abrupt restoration of spring systems or mechanical levers determine the haptic comfort when the switches are pressed.

Haptic pleasantness appeals to both adults and children, and many consumer products are designed to meet these requirements. However, methods for optimizing the haptic pleasantness of mechanical buckling have not been reported in the literature. For example, Gaspar et al. (2017) and Vieira et al. (2017) reported that the difference in the reaction force immediately before and after buckling primarily determines the haptic pleasantness of switches. Hatzfeld et al. (2010) reported that this force difference also influences the hardness, smoothness, and gentleness of the switches. Kosaka et al. (2005) proposed a system for designing mechanical switches so that their reaction force produces the desired affective attributes. Valverde et al. (2019) measured the reaction forces of 18 types of push buttons and defined 20 parameters calculated from the reaction forces. Therefore, earlier studies have examined the effects of stroke (displacement) and reaction force on the subjective evaluation of pressing performance (Colton et al., 2007a, 2007b; Kim and Lee, 2013; Kosaka et al., 2005; Valverde et al., 2019; Wu et al., 2016; Wu and Smith, 2015). Although optimizing designs for the buckling feel based on such an examination may be possible, few studies have demonstrated methods to achieve the optimal feel.

In this study, we experimentally optimized the haptic sensation associated with buckling. Previous studies investigated the antecedents of haptic pleasantness (Hatzfeld et al., 2010; Kim and Lee, 2013; Schütte and Eklund, 2005; Vieira

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et al., 2017; Wellings et al., 2010) and simulated haptic buckling stimuli (Breitschaft et al., 2021; Park et al., 2011; Park et al., 2020; Partk et al., 2022; Sadia et al., 2020; Suzuki et al., 2020; Wu et al., 2016; Wu and Smith, 2015). For example, Park et al. (2011) designed several vibrotactile switch-like stimuli and investigated the preferred vibration patterns. Sadia et al. (2020) successfully simulated three types of mechanical buttons—latch, toggle, and push buttons—using vibrotactile specimens. However, the optimization of the haptic feel for buckling has yet to be reported. In the study with an aim closest to ours, Li et al. (2013) specified the design parameter space of diaphragm-type push-buttons such that the ratio of local maximum and minimum of reaction forces at the moment of buckling was sustained at high values. Although they used finite element models to compute the force ratio, we involve user studies to evaluate the haptic feel, which is formed by the force ratio and other factors.

We employed the response surface method used in quality engineering to optimize the buckling sensation with 3D-printed popping toys as the target object for optimization. The optimization procedures of haptic feel entail prototyping and user-evaluation of actual specimens, and the costs required for experiments are a major concern. The response surface method and related experimental designs are known as cost-effective approaches and save us from conducting an exhaustive search in the parameter space; however, to our knowledge, such optimal designing methods have not been employed for pursuing haptic comfort. In contrast to buttons or switches, the popping toy has no practical function and only its haptic sensations are enjoyed; hence, the popping toy is appropriate for validating the optimization method for buckling pleasantness. The aim of this study was to confirm that an optimization approach based on response curves is applicable for haptic sensations. Our demonstration of the optimization will provide insights to industries for the haptic design of objects such as switches and toys.

Fig. 1 Commercial haptic popping toy. Users enjoy the haptic feel of buckling caused when they press the silicone spherical dome with a fingertip.

2. Specimen: haptic popping toy

Figure 2 shows photographs of the haptic popping toy and a diagram illustrating the dimensions. Popping toys were produced using a 3D printer (From3; Formlabs Inc., USA). Elastic 50A resin (Formlabs Inc., USA) was used for all the popping toys. In this section, the design parameters of the popping toys are described. As regards the haptic sensations of mechanical switches and buttons, the reaction forces caused by pressing them have been frequently discussed. However, many of the parameters defined from the force profiles (Valverde et al., 2019) are not independently controlled. Furthermore, methods to independently control those parameters have yet to be investigated. Hence, we selected the dimensional parameters of the popping toy as its design parameters. Further, we employed surface response methods for parameter optimization. This method enables the determination of the parameter sets in a multidimensional space composed of continuous variables so as to achieve the designated best performance. This method is not suitable for dealing with categorical parameters, and we excluded them as such. For experimental optimization problems involving continuous and categorical variables, the Taguchi method (Taguchi, 1995) has been frequently adopted.

We preemptively created prototypes of the popping toys and investigated the design parameters related to the pressing sensation produced by the toys. Consequently, we selected three parameters: the bottom diameter of the dome, d (mm); the height from the surface of the base to the top of the dome, h (mm); and the fillet, R (mm). The fillet R is the radius of the rounded edge of the dome. The height and diameter can be common design parameters of spherical diaphragms (Li et al., 2013). The thickness of the dome resin is 0.8 mm. The thickness could be important for determining the haptic feel of popping toys; however, we excluded the thickness from the design parameters because of manufacturing problems. For

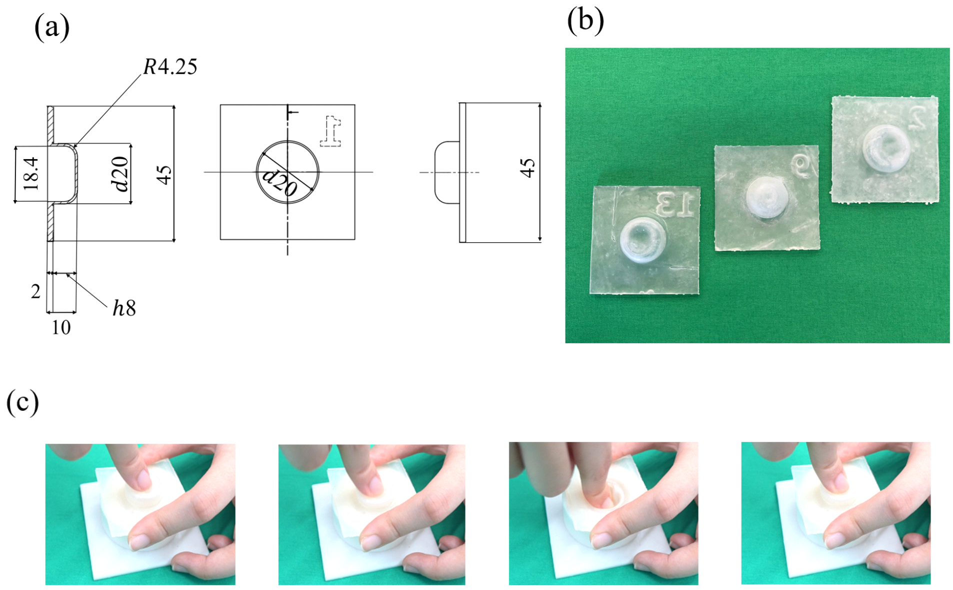

Fig. 2 Haptic popping toy. (a) Drawing with dimensions. From left, cross-sectional, top, and side views. (b) Photograph of three out of 13 popping toys. (c) Experimental scene. The center of the dome is pushed by the fingertip (left picture) until it is buckled (middle picture) and completely turned over, producing a pleasant haptic feel.

example, domes with a 0.6–0.7 mm thickness are easily broken during manufacturing and cleaning processes. Domes of 0.9–1.0-mm-thickness are too stiff to be adopted for popping toys. Given that the resolution of manufacturing is 0.1 mm, we fixed the thickness to be 0.8 mm, considering that this value is the best among feasible values. Notably, because our objective was not to design commercial products, we did not exhaustively investigate all the potentially effective parameters and materials. As aforementioned, we aimed to demonstrate the optimal design of haptic sensations by using the popping toy as an example.

We set the minimum and maximum values of d, h, and R to 15 and 20 mm, 4 and 8 mm, and 0.5 and 8 mm, respectively. The authors and their five colleagues evaluated the prototypes in preliminary experiments and agreed that these ranges would satisfactorily contain the optimal value set. These values are similar to those found in commercially available popping toys (e.g., Go Pop! from Foxmind Canada Enterprises LTD., Canada). Nonetheless, the commercial popping toys employ a hemispherical shape with $d = 2h = 2R \sim 16.5$ mm. The parameter space explored in this study encompasses the parameter set of the commercial popping toys. Further, in our study, R is variable; this allows for the exploration of shapes except for hemispheres.

We employed the Box-Behnken design for the specimen set. The Box-Behnken design and central composite design are typical approaches for optimal design in quality engineering. The major differences between them are the levels of design parameters available and the number of experimental trials. In this study, the number of levels for each parameter was set to three because the ranges of the parameters were small. In this case, the Box–Behnken design led to fewer initial specimens, namely, 13. The values of d, h, and R for the 13 popping toys created based on the Box-Behnken design are listed in Table 1. Specimen 7 cannot be manufactured because the fillet value is larger than the diameter. Therefore, its fillet was adjusted to 7.5 mm.

Table 1 Parameters of 13 popping toys based on the Box-Behnken design. d: diameter of circle (mm), h: height (mm), R: fillet (mm)

Specimen no.	1	2	3	4	5	6	7	8	9	10	11	12	13
d	20	20	15	15	20	20	15	15	17.5	17.5	17.5	17.5	17.5
h	8	4	8	4	6	6	6	6	8	8	4	4	6
R	4.25	4.25	4.25	4.25	8	0.5	7.5	0.5	8	0.5	8	0.5	4.25

3. Experiment 1: optimization of haptic popping toy

3.1. Experimental procedures

The participants pushed the center of the dome of the popping toy in the vertical direction by using the pad of the index finger of their right hand until the dome sank completely, as shown in Fig. 2 (c). Participants were allowed to push it repeatedly until they had a definitive opinion. Typically, three to five iterations were required for each trial. During the experiment, the participants wore sunglasses with masking tape attached to avoid visual discrimination by restricting them from fully seeing the specimens. Further, the participants were encouraged to employ similar pressing motions for all the specimens.

For each specimen, four evaluation items were rated: overall evaluation, ease of pushing, buckling, and stiffness. The overall evaluation was defined as the haptic pleasantness of the entire pushing experience. The ease of pushing refers to how easy it was for the user to push and sink the dome completely. Buckling was defined as the pleasantness when the dome buckled. The stiffness was defined as the hardness of the dome. Buckling and stiffness were adopted from a study by Kosaka et al. (2005), in which seven types of affective attributes were used to evaluate mechanical buttons. We selected only stiffness and buckling, which is referred to as clicking in the study by Kosaka et al. (2005), because the other five attributes, such as smoothness and clarity, were inapplicable to popping toys. Similar attributes, including hardness and crispness, were used by Hatzfeld et al. (2010) and Miyairi et al. (2022) to evaluate the haptic feel of buttons. Furthermore, we found that some participants with large fingertips could not easily press and sink the dome when its diameter was small. Hence, we introduced another evaluation item, namely, the: ease of pushing.

Each of the four items was rated on a scale from 1 to 9. For the overall evaluation and buckling, 1 and 9 were labeled as “non-pleasant” and “pleasant,” respectively. For the ease of pushing, 1 and 9 corresponded to “difficult” and “easy,” respectively. For the stiffness, 1 and 9 corresponded to “soft” and “stiff,” respectively. Considering the relative difficulty of assessment, the rating task was performed referring to a reference. For the overall evaluation, ease of pushing, and buckling, Specimen 5 was used as the reference, and its scores were set to five. Each participant tested 13 specimens in a randomized order in a single set. Three sets were performed, totaling 39 trials.

3.2. Participants

Ten university students (four of whom were females) participated in the study after providing written informed consent. The participants were unaware of the study objectives.

3.3. Ethical statement

The study protocols were approved by the Institutional Review Board of the Hino Campus, Tokyo Metropolitan University (#22-31).

3.4. Analysis

We normalized (z-score) the scores of each evaluation item for each participant. The mean scores of three repetitions were used to compute a response surface. The response surface was established in the design parameter space for each evaluation item. We adopted a stepwise multiple regression analysis method with the explanatory variables d (diameter), h (height), R (fillet), and their quadratic and interaction terms. The initial model was quadratic, with nine explanatory variables: d, h, R, d^2, h^2, R^2, $d \times h$, $d \times R$, $h \times R$. The least significant variable in terms of p-value was removed from the model at each step until all remaining variables were significant at $p < 0.05$. This process was performed for each of the four evaluation parameters: overall evaluation, buckling, ease of pushing, and stiffness. In addition, we investigated the relationship between the overall evaluation and the three evaluation items using multiple regression analysis.

3.5. Results

Figure 3 shows the means and standard errors of the overall scores of specimens. Specimen 11 was judged most pleasant, followed by Specimens 13 and 9. Table 2 lists the significant explanatory variables for each of the four evaluation items. The significant explanatory variables were d, $d \times h$, $d \times R$, d^2, h^2, and R^2 for the overall score; d, $d \times h$, d^2, and h^2 for the buckling score; d, h, $d \times R$,and d^2 for the ease of pushing score; and h, $d \times R$, d^2, and h^2 for the stiffness score. The adjusted R^2 values were 0.35, 0.18, 0.64, and 0.63 for the overall, buckling, ease of pushing, and stiffness scores, respectively. The correlation coefficients between the observations and estimations were moderate at 0.61 and 0.45 for the overall and buckling scores, respectively, and they were strong at 0.80 for both the ease of pushing and stiffness scores.

Table 3 presents the results of the regression analysis to estimate the overall evaluation score, using the scores of buckling, ease of pushing, and stiffness as explanatory variables. The buckling and ease of pushing scores were the most important for the overall evaluation. The adjusted R^2 value was 0.69, and the correlation coefficient between the observations and estimations was strong at 0.84.

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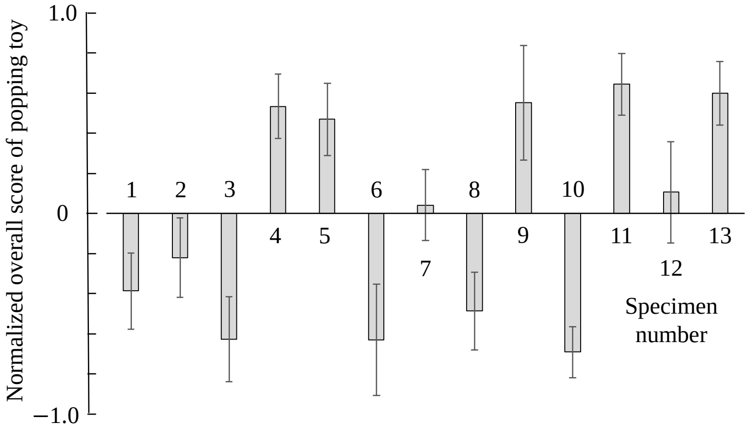

Fig. 3 Mean and standard errors of the overall scores of specimens. Greater values are more pleasant.

Based on Tables 2 and 3, the structure of the overall evaluation was determined, as shown in Fig. 4. The figure shows the significant links found in the multiple regression analyses.

Table 2 Partial regression coefficients and p-values of the significant explanatory variables for each evaluation item: (a) overall evaluation, (b) buckling, (c) ease of pushing, and (d) stiffness. Only statistically significant coefficients are listed.

(a) Overall evaluation

Parameter	Coefficient	p-value
d	2.83	5.77×10^{-5}
$d \times h$	0.042	0.0061
$d \times R$	0.015	6.0×10^{-4}
d^2	−0.090	1.7×10^{-5}
h^2	−0.073	1.2×10^{-3}
R^2	−0.017	0.046

(b) Buckling

Parameter	Coefficient	p-value
d	2.32	0.0031
$d \times h$	0.077	1.5×10^{-5}
d^2	−0.081	4.0×10^{-4}
h^2	−0.12	9.1×10^{-6}

(c) Ease of pushing

Parameter	Coefficient	p-value
d	1.30	0.013
h	−0.16	7.82×10^{-8}
$d \times R$	0.011	0.015
d^2	−0.037	5.5×10^{-26}

(d) Stiffness

Parameter	Coefficient	p-value
h	1.088	2.0×10^{-4}
$d \times R$	−0.012	5.5×10^{-26}
d^2	−0.002	1.5×10^{-3}
h^2	−0.90	2.0×10^{-4}

Table 3 Partial regression coefficients and p-values to estimate the overall evaluation score using the other evaluation variables.

Evaluation item	Coefficient	p-value
Buckling	0.566	2.55×10^{-19}
Ease of pushing	0.507	1.30×10^{-10}
Stiffness	0.020	0.79

4. Experiment 2: post-hoc experiment

4.1. Specimen: optimally designed popping toy

We created another popping toy using the optimized parameters based on the results of Experiment 1. On the basis of Table 2 (a), the response surface formula for the overall evaluation is expressed as

$$\text{Overall evaluation} = 2.83d + 0.042d \times h + 0.015d \times R - 0.090d^2 - 0.073h^2 - 0.017R^2 - 23.8. \quad (1)$$

At the maximum point of the response surface, the partial derivatives of d, h, and R are zero. The three simultaneous equations were solved and the optimal parameter set was determined to be $d = 17.2$ mm, $h = 3.3$ mm, and $R = 7.6$ mm. The values of diameter and fillet are within the parameter space used in Experiment 1. The height is out of the range of the initial specimen set ($4.0 \leq h \leq 8.0$). Nonetheless, the difference between the lower limit of the height (4.0 mm) and 3.3 mm is only 0.7 mm; hence, we used $h = 3.3$ mm. The parameters of the optimally designed popping toy were similar to those of Specimen 11, for which $d = 17.5$ mm, $h = 4$ mm, and $R = 8$ mm.

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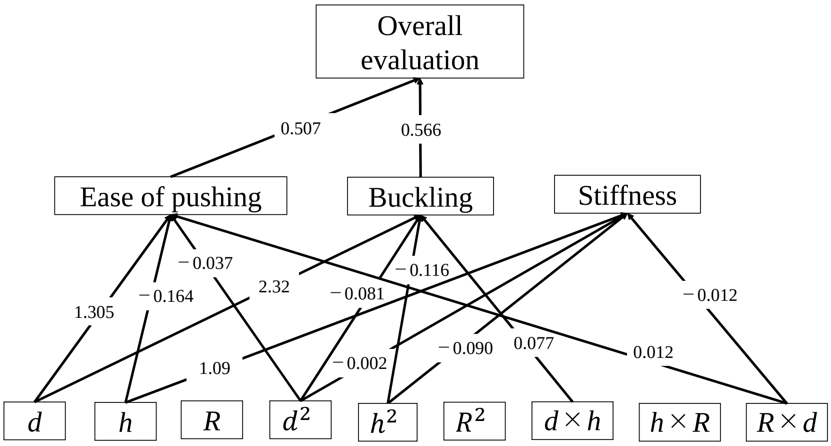

Fig. 4 Structure of the overall evaluation score and other variables based on Tables 2 and 3. The values of the links are the partial regression coefficients at $p < 0.05$. R, R^2, and $h \times R$ do not significantly influence the variables in the middle layer.

4.2. Experimental procedures

We compared the optimized popping toy and Specimen 11, which had the largest overall evaluation score among those used in Experiment 1. The participants pushed these two popping toys freely while wearing sunglasses with masking tape. They selected the specimen with the highest overall haptic pleasantness as the popping toy. No time limitations were set; however, all participants completed the experiment within one 1 minute.

4.3. Participants

We considered 0.75 : 0.25 as a practically meaningful preference bias for the two popping toys and estimated the number of participants (n) such that the difference in proportions between 0.75 and the chance level, 0.5, was found to be significant at $p < 0.05$ following the one-sample proportion test:

$$1.96 < \frac{(0.75 - 0.5)\sqrt{n}}{\sqrt{(0.5 \times (1 - 0.5))}}. \tag{2}$$

The minimum integral n value required to satisfy this equation is $n = 16$; hence, we set the number of participants to be greater than 15. Twenty-one university students (in their 20s; six females) participated in the post hoc experiment. The participants were unaware of the study objectives and provided written informed consent before the experiment.

4.4. Analysis

The proportion of participants who selected the optimally designed popping toy for greater haptic pleasantness was calculated. We then investigated whether the proportion was significantly different from chance (i.e., 0.5) using the z-test.

4.5. Results

Twelve of the 21 participants selected the optimally designed popping toy for better haptic pleasantness. The proportion of preferences for the optimally designed popping toy was not significantly higher than that for Specimen 11 ($z = 0.65$, $p = 0.55$), indicating that the optimally designed popping toy was preferred as much as Specimen 11.

5. Discussion

The results of Experiment 2 showed that the optimally designed popping toy was as comfortable as the most haptically pleasant specimen in Experiment 1. In quality engineering, this phenomenon is typical when the parameter space is small. For example, certain errors between the set and performance measures of the optimized prototype should be accepted (Krishnaiah and Shahabudeen, 2012). In this study, the parameters of the optimal popping toy were accidentally close to those of Specimen 11, which had the highest overall evaluation score among the initial specimen set. Therefore, we did not observe any meaningful performance improvement using the optimal design. This does not indicate that the optimal design used in quality engineering is not applicable to haptic sensations. The optimally designed popping toy was selected as often as Specimen 11 in Experiment 2, and the effectiveness of an optimization approach was demonstrated.

We found that the overall haptic comfort was determined by the buckling and ease of pushing. It is natural for buckling to affect the haptic comfort of popping toys because they are made to provide a pleasant tactile sensation when buckling. Additionally, it is reasonable for the ease of pushing to determine the overall evaluation. It is more difficult for a dome with a smaller diameter to be pressed and reach the bottom, leading to frustration. The rationale for stiffness not affecting the overall haptic pleasantness is debatable. The tactile pleasantness of a switch is mainly determined by the difference in the reaction force immediately before and after buckling, and stiffness is not the dominant antecedent for determining it (Veira et al., 2017). Popping toys resemble push switches regarding their haptic feel. Hence, stiffness may be a secondary factor in determining haptic pleasantness.

As in Section 3 and Fig. 4, we analyzed three evaluation items or factors that could potentially lead to haptic pleasantness. Among them, buckling, which is the pleasantness felt at the moment of buckling of the dome, was not well explained by the set of design parameters, with an R^2 value of 0.18. This is attributable to the large individual differences. We found that the pooled variance σ^2 of the evaluation scores of buckling among the participants was greater than those of ease of pushing and stiffness. Table 4 lists the ratios of variances, which are F-statistics, and their corresponding p-values for the two-tailed tests. The hypothesis of the equality of variances for $\sigma^2_{\mathrm{buckle}}/\sigma^2_{\mathrm{push}}$ and $\sigma^2_{\mathrm{stiff}}/\sigma^2_{\mathrm{buckle}}$ were rejected, indicating that the variance of the scores of the buckling was greater than those of ease of pushing and stiffness. There are two potential reasons that the pleasantness of buckling is not well predicted by the design parameters of the popping toy. First, the pleasantness may depend on the finger's pressing motion. In our experiment, the finger motions of the participants were not measured; however, the analysis on their individual differences may help understand the pleasantness of buckling stimuli. In particular, we speculate that the individual differences in finger velocity is a potential cause. When the velocity is slow, relatively stiff domes tend not to produce pleasant haptic feel. In our experiment, finger velocities were not controlled among the participants; hence, the same specimen might have not been equally rated by different participants. Second, distinction between individual preferences may have been another relevant aspect. A clustering analysis involving a sufficient number of participants may suggest the presence of such individual preferences. Thus far, such differences have rarely been discussed by prior studies on mechanical switches and buttons. These human factors should be elucidated in the future.

Table 4 Test of equality of variances between the scores for buckling, ease of pushing, and stiffness.

Combination of variances	Ratio of variances	p-value
$\sigma^2_{\mathrm{buckle}}/\sigma^2_{\mathrm{push}}$	$F(129, 129) = 1.92$	2.5×10^{-4}
$\sigma^2_{\mathrm{push}}/\sigma^2_{\mathrm{stiff}}$	$F(129, 129) = 0.881$	0.47
$\sigma^2_{\mathrm{stiff}}/\sigma^2_{\mathrm{buckle}}$	$F(129, 129) = 0.592$	3.1×10^{-3}

Although this study did not measure the reaction force and displacement of the dome during buckling, the correspondence between the dynamic patterns of the reaction forces and the haptic sensations is important, as indicated in earlier studies (Gaspar et al., 2017; Hatzfeld et al., 2010; Kosaka et al., 2005; Vieira et al., 2017; Weir et al., 2004). In the future, optimization must be performed from the viewpoint of the reaction force. However, thus far, a method to independently control multiple parameters that are defined from the force-displacement profile has not been established. Optimization of the reaction force may require several more research stages. Furthermore, multi-objective optimization should be pursued because the most important role of switches is to deliver a sense of mechanical transition and prevent the misuse of human-machine interfaces. An appropriate balance among the multiple objectives should be considered when applying the optimization to mechanical switches.

6. Conclusion

Although previous studies have investigated the cause of the haptic pleasantness of buckling, they have not attempted to obtain an optimal design. In this study, we realized the optimal design of a popping elastic dome toy by using the response surface method. The optimized popping toy was as pleasant as the specimen that was judged to be the most comfortable among the 13 specimens evaluated in the experiment. Furthermore, for popping toys or buckling domes, the haptic sensation at the moment of buckling and ease of pushing determined the overall haptic evaluation. The optimization of haptic pleasantness caused by buckling or switch-like mechanical flips is useful in various industries, including the automotive industry (Colton et al., 2007a; Stamer et al., 2020; Vieira et al., 2017), and the response surface method is promising for this purpose. To further verify the optimization approach, the same or similar optimization approaches must be applied to other products, such as buttons and switches.

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