Design Method of 3D-Printable Ergonomically Personalized Stabilizer

Ryota Kawamura(✉), Kazuki Takazawa(✉), Kenta Yamamoto(✉), and Yoichi Ochiai(✉)

University of Tsukuba, Digital Nature Group, Tsukuba, Japan
`ryota.kawamura@digitalnature.slis.tsukuba.ac.jp`

Abstract. In photography and videography, it is a challenge to align a sight toward the target continuously and steadily, as considerable practice and experience are required. Blurry photographs are often captured by camera users who lack the necessary skills. To address the problem, stabilizers have been developed. However, conventional stabilizers involve a steep learning curve because they are designed to be mass produced, and thus not tailored according to an individual. We herein present the design method of a three-dimensional printable personalized stabilizer. It is optimized ergonomically through topology optimization, which is a typical method to optimize the shape of materials.

Keywords: Digital fabrication · Personalization · Design · Personal fabrication

1 Introduction

In photography and videography, it is a challenge to align a sight toward the target continuously and steadily, as considerable practice and experience are required. Blurry photographs are often captured by camera users who lack the necessary skills. To address the problem, stabilizers have been developed. Conventional stabilizers involve a steep learning curve because they are designed to be mass produced, and thus not tailored according to an individual. For example, in filming a location, large equipment or considerable manpower have been used to move a photographer smoothly, primarily because conventional stabilizers have less customizability for various uses. It is noteworthy that stabilizers for professional users are heavy, in general, that a photographer cannot perform any actions other than photographing. The spread of image sharing applications has resulted in increased camera users. Non-personalized stabilizers bring out the result to lack of user experiences. For example, some users suffer from holding a camera with their hands for a prolonged time. To achieve the goal where all users can operate stabilizers comfortably and enjoy photographing without any stress, we must build a design framework of personalized stabilizers without any costs such as transport or human power produced by a simplified manufacturing

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line that can be customized without any stress. Hence, it is necessary to conduct shape-optimization based on a user's physical features for personalized stabilizers, and form it through digital fabrication technologies. The system formulates the problem internally as topology optimization, and subsequently forms it using three-dimensional (3D) printing technologies using different materials.

2 Related Work

2.1 Commercial Strategies for Supporting Photography

Currently, camera photography and videography can be observed in some situations such as when people capture a photograph of everyday life or when a professional photographer shoots a film. To support photography and videography, camera shake correction techniques are now available on many cameras, which benefits users. Camera shake corrections are divided into two methods: a *software-based* approach that realizes correction with electronic calculations such as electronic image stabilizing, and a *hardware-based* approach that realizes the correction with optical image stabilization. Thus, each image stabilizing method installed on camera presents its own advantages. However, disadvantages also occur for these methods, in that users cannot receive any photography support unless they own the camera because different cameras involve different image stabilizing techniques. Old and cheap cameras most likely do not possess any of these techniques; hence, the quality of photography and videography would depend on a user's skills.

Electronic image stabilization techniques installed on camera can be defined as a *software-based* approach, and numerous investigations based on software have been conducted [6,13,14].

Meanwhile, optical image stabilization techniques installed on camera can be defined as a *hardware-based* approach, and numerous investigations based on hardware have been conducted [4,8].

Commercial stabilizers have been developed to avoid such a hardware dependency, as shown in Fig. 1. A stabilizer is a photographic instrument directly installed on the body of a photographer. It enables a smooth operation even with a large camera. Many commercial stabilizers can reduce camera shake from handheld devices to devices attached to users. Although a handheld stabilizer is light, it lacks stability. Therefore, professional photographers tend to use a heavy stabilizer. Because they must operate it for a long time, it leads to user fatigue. Thus, the weight of a stabilizer has been related to user fatigue. Currently, brushless gimbals have been used to reduce camera shake and user burden. A steadicam is a conventional device to support camera users and is slightly heavier, whereas brushless gimbals are lighter than a steadicam because their gimbals are controlled computationally. Thus, this device depends on the proficiency of the user, and subsequently the scope of use is limited to professional photographers. To our knowledge, no method exists that specializes in designing stabilizers for amateur individuals, and they are only shared as 3D models created by volunteers in the design repository.

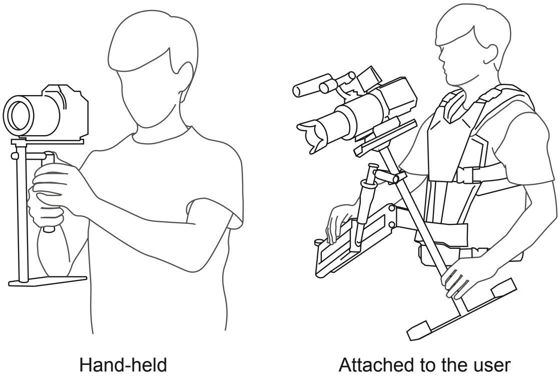

Fig. 1. Examples of 2-type camera stabilizers. Left: a hand-held device. Right: a device attached to the user to fix a camera for a long time in situations like a film shooting.

2.2 Optimization with Digital Fabrication

The spread and development of computers have diversified computational design methods. Further, the affinity between digital fabrication and optimization is high, thereby resulting in the development of some products. Koyama et al. presented a computational design method to automatically optimize and create a 3D-printable connector between two different objects [7]. In their study, they provided a simple user interface to users so that they would not be confused. They were only required to adjust the fix-position of two objects and the length between them, and they could choose the suitable design from presented candidate designs. We also adopted the concept to allow end-users to design a personalized stabilizer easily.

Fabrication researchers are also interested in the internal mechanism of 3D objects. Several studies have been conducted widely on balancing 3D objects under certain circumstances such as underwater [10,16], in air [15], etc. Changing the internal mechanisms of 3D objects also enabled them to stand on a plane [11,16].

2.3 Topology Optimization

Shape optimization is important in computational design. In particular, topology optimization is a typical shape-optimization method. Several professional software are available to support the generative design in the market such as ANSYS[1] and the components in the framework of Grasshopper plugin[2,3]. Topology optimization, in which inefficient materials are removed iteratively from a

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[1] https://www.ansys.com/products/structures/topology-optimization (Last accessed: 2019-02-15).

[2] http://www.grasshopper3d.com/forum/topics/stress-topology-optimization-with-millipede (Last accessed: 2019-02-15).

[3] https://www.food4rhino.com/app/ameba-rhino (Last accessed: 2019-02-15).

Fig. 2. Left: All of parts we prepared. They consists of a monopod, harness, bungee code, and 3D-printed components. Center: assembly phase of these parts. Right: the user is equipped with our instrument.

structure while efficient materials are added to the structure simultaneously, obtains the best layout of materials within a limited design space, and maximizes the system performance. Optimized structures sometimes exhibit limitations regarding shape, thereby rendering them difficult to reproduce on an industrial scale. However, a breakthrough in reproduction was achieved from digital fabrication [1]. The design method to optimize shape by topology optimization has often been investigated in human-computer interaction. For instance, Chen et al. [2] presented a user-driven generative design method using topology optimization. Kazi et al. [5] also used topology optimization and function for a sketch-based generative design. We also used topology optimization in the method describe herein this paper, which is on the Grasshopper as an add-on. When using the add-on and realizing topology optimization on Grasshopper, some components functions are used as the inputs of topology optimization. Thus, our method of conducting topology optimization is conventional from the viewpoint of direct inputs.

3 Exo-Balancer

In this section, we introduce the Exo-Balancer, our previous design method for a personalized stabilizer, and the results. Next, we enumerate some issues that are to be addressed. Subsequently, we describe the implementation in detail.

3.1 Implementation

In this section, we introduce our implementation, which is divided into two parts: calculation that considers the moments of forces between the user and some instruments, and personalized fabrication using the simulated result. Our system consists of a calculation to investigate the suitable fixed position and some instruments to mount a camera. These instruments include a harness, monopod, and camera, two bungee cords, and an assembly of connectors printed with a 3D printer (see Fig. 2 center). Figure 2 (left) shows the model of components between a harness and monopod.

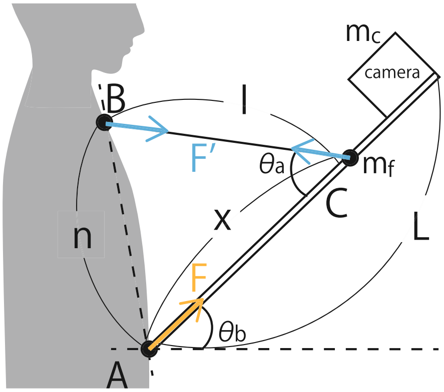

Fig. 3. Simple configuration image of our instrument. This image includes the applied forces, the masses of a few instruments, and the angles when the user is equipped with our instrument.

Calculation Using Body Data. Our goal is to personalize a stabilizer such that users can capture photographs without any stress. Hence, we focus on the moments of forces. We present a design method to obtain a suitable position for each user from a balance relation between forces and moments according to their body data and the fixed angles of an object. First, users input the length from their shoulder to lumbus (its value is n, see Fig. 3) as their basic body data, the angle θ_b that sets the upward-facing horizontal as positive, and fixes a camera. According to the horizontal and vertical equilibrium of forces, the following equations are obtained:

$$F = m_f g \cos\theta_b + F' \cos\theta_a + m_c g \cos\theta_b \tag{1}$$

$$F' \sin\theta_a = m_c g \sin\theta_b + m_c g \sin\theta_b \tag{2}$$

where F is the force on the point-on-contact between a harness and monopod, while F' is that on the point-of-contact around the shoulder of the user. L is the length from a harness to a camera, while x is the length from a harness to the point that supports a monopod; l is the length from point to A. We ask the user to hold a camera in advance, and measure the distance from the camera position to where the harness is to be attached (its value is L, see Fig. 3). We apply L to the measured value. As shown in Fig. 3, θ_a is the angle between the line segment from B to C and the line segment from A to a camera. The moment of forces around C is as follows:

$$\frac{x-L}{2} m_f g \sin\theta_b = (L-x) m_c g \sin\theta_b \tag{3}$$

From Eqs. (1) to (3), we gain equations about x as follows:

$$x = \frac{(2m_c + m_f)L}{2(m_c + m_f)} \tag{4}$$

We define the equation $F = F'$ as the requirement that minimizes the forces on the user body and calculate them on Unity[4]. Subsequently, we solve the following equation:

$$2l^3 + nl^2 - 2l(n^2 + x^2) - n(x^2 - n^2) = 0 \tag{5}$$

Our system optimizes the two equations above by inputting x and l, which are based on specific user values. Thus, we obtain the optimally fixed position of a camera for the users.

Assemble Some Parts Using Calculated Results. Next, the users externalize the data to the physical world. First, we attach the harness, which is typically used to set an instrument such as a camera, to the body. A harness comprises a mounting plate; thus, we set a monopod to the mount (see Fig. 2 right). We printed out the models on a 3D printer (5th generation printer) using regular polylactic acid filaments. We set its infill rate to 100% because it must withstand some forces and support some parts.

3.2 Evaluation

In this section, we describe the experimental evaluation of our approach. Our evaluation involved a qualitative evaluation to interview the participants in our experiment about the practicability of our instrument and a quantitative evaluation based on a three-axis acceleration sensor to measure the shakiness of a camera. First, we asked the participants to capture videos for 30 s to verify the effect of our personalization. The participants conducted this phase four times: hold a camera by their hands, hold a camera with our method, hold a camera with our method while changing x slightly from the calculated results. Thus, we investigated whether our design method had resulted in personalization. Next, we conducted an interview and some questionnaires. In addition to the quantitative evaluation, we compared the impact on a camera with that on our instrument as a qualitative evaluation. We measured the values on a three-axis acceleration sensor attached to a camera and compared them.

Participants. To verify the practicability of our method, we recruited college students (1 female, 7 males) as participants. They had different physique. They were aged between 18 and 25 years (M = 20.4, SD = 2.0) and were not familiar with the stabilizer of a camera.

Experimental Procedure. To calculate the parameters for personalization, we first equipped the participant with a harness and adjusted the length to fit to their bodies. We measured two lengths: one is between the shoulder and the mount of a harness (n, as mentioned in the section, "Simulation using body data"), and the other is between the mount of a camera and the mount of a

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[4] https://unity3d.com (Last accessed: 2019-02-15).

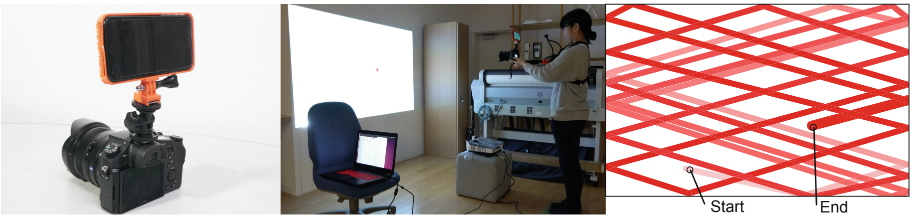

Fig. 4. Left: the camera used in our experiment. Center: iPhone 6 attached to the camera in order to measure the gravitational acceleration from its acceleration sensor inside it. Right: a scene of our experiment. (Color figure online)

harness (L, as mentioned in the section, "Simulation using body data"). To define L, we asked the participants to hold a smartphone when they capture a photograph. We input these values for the participants' own data and calculated x and l. Finally, we assembled the parts and equipped them on the body of the participants based on these values. We projected a video in which a red ball was bouncing onto the wall for 30 s. In our experiment, the participants continued with shooting such that he/she could observe the ball in the middle of the angle of view (see Fig. 4 center). It is noteworthy that the ball speed changes randomly when it bounces off the wall (see Fig. 4 right).

Usability in Personalizing Shootings. As a quantitative evaluation, we interviewed the participants. The purpose of this interview was to reveal how the users felt when using our instrument. To investigate the usability and enjoyability, we asked them to rate each question in a five-point Likert scale, from "strongly disagree" to "strongly agree." In addition, we asked for details with free-description questions. We used the two-tailed Wilcoxon signed-rank test, which is non-parametric method and evaluated at an alpha level of 0.05. Scores of each question were analyzed on a five-point Likert scale. We also analyzed two cases derived from our method similarly when we changed the value of x deliberately to verify the propriety of our method (see Fig. 5, Q1–Q4). In addition to these questions, to investigate the usability, we prepared two questions regarding the enjoyability (see Fig. 5, Q5, Q6). Finally, we asked the participants for details with free-description questions.

3.3 Results

Figure 5 shows the results from all six questions. These questions aim to reveal the usability (Q1–Q4) and enjoyability (Q5, Q6). The first question pertained to the operability when the participants captured a photograph. In the conventional style, they are required to hold a camera at all times with both hands while bending a little and look into the finder. However, our method is different, in that we only need them to hold a camera with one hand and operate the other

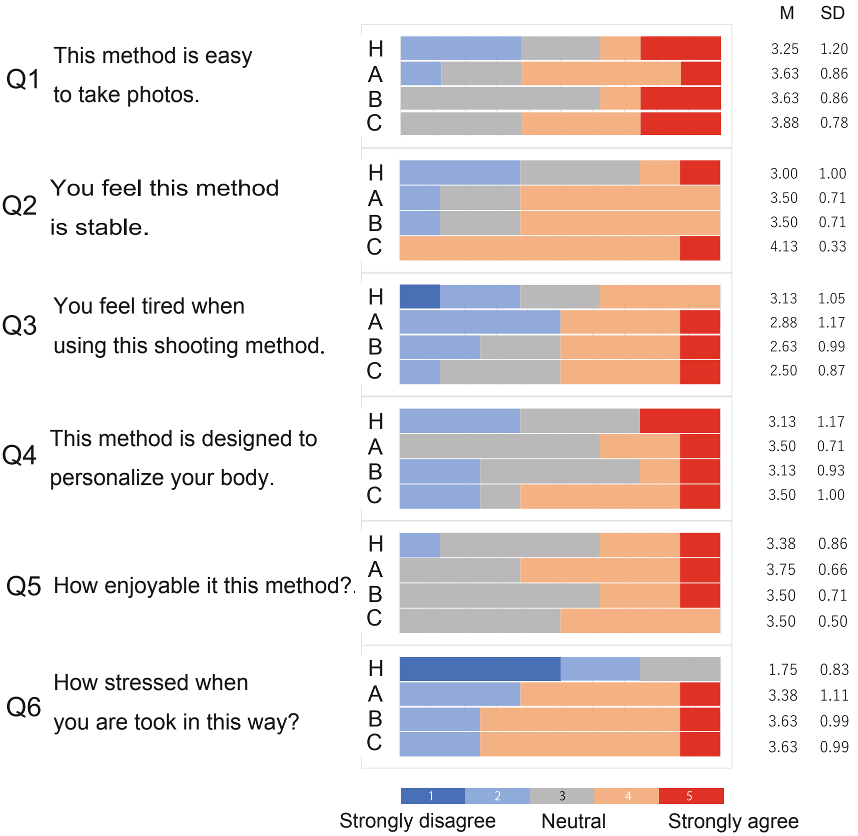

Fig. 5. Rating the usability of personalizing shootings compared to another 3 methods. Our instrument is used in method A. In method B, x is set to plus 5 cm. On the other hand, it is set to minus 5 cm in method C. Each question is scored on a 5-point Likert scales.

instruments with another hand while grasping a monopod. The Wilcoxon signed-rank test demonstrated no statistical significance between methods A and H ($Z = -0.79$, $p > 0.05$), A and B ($Z = 0.00$, $p > 0.05$), and A and C ($Z = -0.63$, $p > 0.05$).

The second question pertained to the stability when the participants captured a photograph. We focused on whether the participants felt stable to explore the usability. The Wilcoxon signed-rank test demonstrated no statistical significance between methods A and H ($Z = -1.89$, $p = 0.06$), A and B ($Z = -1.19$, $p > 0.05$), and A and C ($Z = 0.00$, $p > 0.05$).

The third question pertained to the fatigue when the participants captured a photograph. Fatigue is an important element while investigating the usability. Operability and stability are considered to reduce significantly when fatigue increases. The Wilcoxon signed-rank test indicated no statistical significance between methods A and H ($Z = -0.42$, $p > 0.05$), A and B ($Z = -0.54$, $p > 0.05$), and A and C ($Z = -0.83$, $p > 0.05$).

The fourth question pertained to the personalization of participants. The definition of personalization is obscure; thus, we asked them to determine whether these methods were designed for personalizing their bodies. The Wilcoxon signed-rank test demonstrated no statistical significance between methods A and H ($Z = -1.00$, $p > 0.05$), A and B ($Z = -1.13$, $p > 0.05$), and A and C ($Z = 0.00$, $p > 0.05$). Unlike Q1, Q2, Q3, and Q4, we set two questions to understand the participants' enjoyability. We verified the enjoyability from different viewpoints.

The fifth question pertained to the viewpoint of the photographer. For instance, some people are motivated to capture a photograph to satisfy their desire in using an exclusive camera, while others are motivated by the opportunity to communicate with friends through an image-sharing application. Thus, we must investigate the positive effect of our method in sustaining people motivation in photography. The Wilcoxon signed-rank test demonstrated no statistical significance between methods A and H ($Z = -1.34$, $p > 0.05$), A and B ($Z = -1.41$, $p > 0.05$), and A and C ($Z = -1.00$, $p > 0.05$).

Meanwhile, the sixth question was based on the viewpoint of the participant. People tend to be daunted when surrounded by large photographic equipment. Meanwhile, they are often relaxed when captured with a smartphone. Thus, we must confirm that our method does not cause mental stress. The Wilcoxon signed-rank test demonstrated no statistical significance between methods A and B ($Z = -1.00$, $p > 0.05$), and A and C ($Z = -1.00$, $p > 0.05$). Meanwhile, a statistical significance exists between methods A and H ($Z = -2.41$, $p > 0.05$). Overall, all the results are attributed to insufficient power.

In addition, according to the participants' personal opinions from the free descriptions, a few participants felt stressed when they captured a photograph using our method. The majority opinions are provided below. P (participant) 7: "*I felt slightly nervous to be targeted by devices that I have not seen". In method B, a participant struggled at capturing an upper photograph.* P8: "*When I tried to capture an upper photograph, I felt inconvenienced because I had to bend my body backwards.*" In method C, a few participants felt a slight tightness when equipped with the instrument. P2: "*It was difficult to capture pictures on the bottom because my body was pulled up.*" P4: "*I felt a monopod sticking in my chest and it was slightly painful when I was equipped with the instrument.*" P6: "*The mounted position of the camera is slightly far from me when using methods A to C; therefore, I felt the weight. However, it was relatively easy to operate the instrument because its distance was the shortest in these methods.*" P7: "*I felt tightness and discomfort around my chest.*"

Analysis of Each Shaky Phenomenon. In addition to a quantitative evaluation using the Likert scale, we conducted a qualitative evaluation that analyzes the values of acceleration sensors that were built into an iPhone. The application

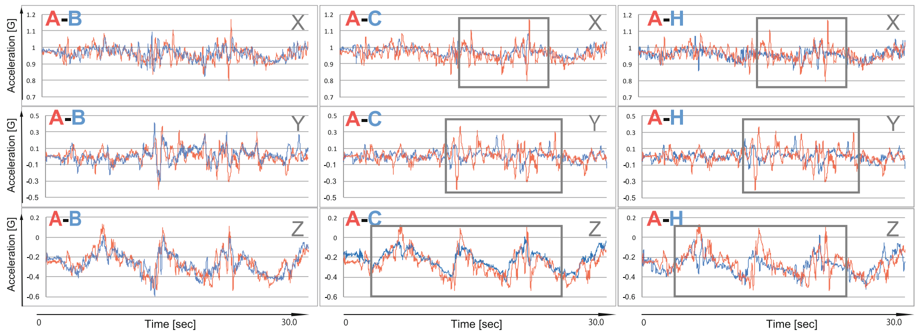

Fig. 6. Results from captured 3-axis position of a camera. Note that graphs of x-axis, y-axis, and z-axis are shown separately in order to compare each method. Besides, red line represents method A and blue line do the others, and black frames do the areas that surround the characteristic range of difference between 2 methods. (Color figure online)

we used for this user study was AccelerationLogger[5]. We attached iPhone6 to the top of a camera (see Fig. 4 left). The data of the participant are shown in Fig. 6, in which the difference in values among the methods was remarkable. In comparison with methods A and H or A and B, a slightly difference was observed. However, we found an interesting difference in comparison with methods A and C. The shake from method C was reduced on all axes rather than that from method A. As described in the next section, method C contributed to the improvement in operability while imposing a burden on the user by reducing x.

3.4 Limitations and Discussions

Through the user study, we asked the participants and verified the usability and enjoyability. Consequently, we found the areas for improvement: reselection of equipment and expansion of experimental situation. Our quantitative evaluation revealed that method C was the most appreciated. Method C is less 5 cm from the value of x, which was calculated, and the reason that the participants appreciated can be attributed to the harness usage. In our experiment, we used a rubber harness because we wanted to detract from the participants' wearability and maintain their lightness as much as possible. However, rubber expands and contracts easily; therefore, a monopod was set slightly looser than the simulated result in method A. Consequently, the score of the five-point Likert scale revealed that method C was the most appreciated by the participants. Another limitation of this study is that our instrument cannot include all participants. Further, x was a few centimeters larger or smaller than the range of our instrument when we experimented one strapping man and one smallish woman. Henceforth,

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[5] https://itunes.apple.com/jp/app/id340777156 (Last accessed: 2019-02-15).

the fundamental reselection of the ready-made instruments or selecting them ourselves using digital fabrication tools such as a 3D printer and laser cutter result in enhanced practicability.

Meanwhile, through our qualitative evaluation, a camera held in a participant's hand reduced the shake the most. Our study is at the prototype stage of achieving the personalized design method; therefore, we focus on exploring the design method for personalization to adapt to the user body and enrich user experience further. Thus, we do not focus on stabilizing more than the existing stabilizers. However, the prototype presented herein may be useful at times, for instance, when a user captures a photograph when they are not standing steadily. We conclude that this approach offers great promise to be useful under such a situation and can improve the performance as a stabilizer.

3.5 Summary

Exo-Balancer is the rudimentary design method for a personalized stabilizer. Based on their physical data, it calculates and presents one of the best fix-positions for users to operate comfortably without any stress. In exploring the position, we considered the moments of forces between the users and equipment such as a harness, monopod, and camera, two bungee cords, and some connectors generated by 3D printers. Subsequently, we recruited participants of different physiques and obtained some results from the quantitative evaluation based on three-axis acceleration sensors on the camera, as well as a qualitative evaluation based on the statistical analysis of the questionnaire.

1. **Low durability because of the property of ready-made goods.** A harness is a typical photography-assisting tool; however, the part that is attached to the body stretches when loads are added because it is made of rubber. Therefore, a camera mounted on a stabilizer generates a large torque, resulting in low usability.
2. **Low adaptability for physically characterized people.** Ready-made goods are not necessarily customable especially when their specifications are limited. In our method, for example, it is impossible to adjust an equipment (e.g., monopod length) slightly when our participants are extremely fat or small.
3. **Low stabilizing ability.** To our knowledge, Exo-Balancer was the first to explore the design space to combine digital fabrication with personalization in producing a stabilizer. Therefore, we first focused on building the whole structure without applying loads compared to conventional commercial stabilizers. Thus, we provided the users an opportunity to experience it as a simple prototype, and expected a specific stabilization mechanism to be the next step.

4 New Approach

We adopted topology optimization, the typical shape-optimization method, as our new approach to address *issue1* and *issue2* described above. We aim to realize

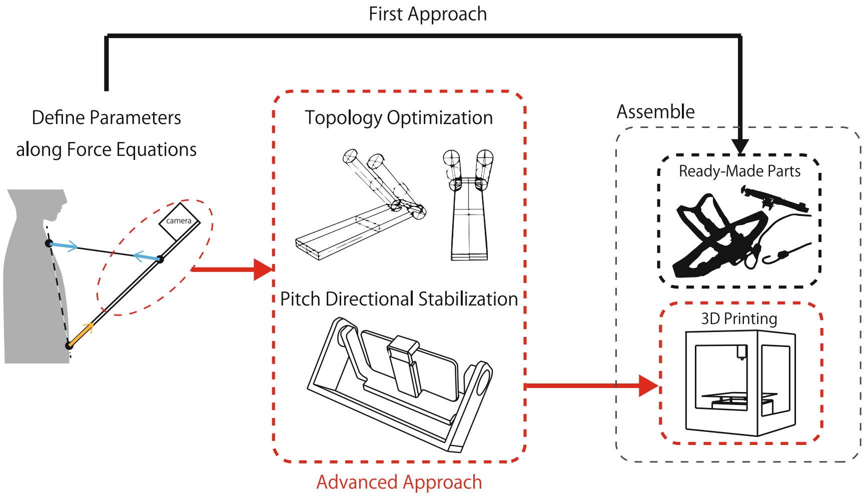

Fig. 7. System overview.

a high optimization and end-to-end output by shifting the size optimization of ready-made goods into computational shape-optimization while maintaining the mechanical constraints proposed previously (see Fig. 7). Regarding *issue3*, we described the structure that enabled pitch directional stabilization when using a compact camera.

4.1 Topology Optimization

First of all, *structural domains* mean the smooth area occupied by structures. In topology optimization, we introduce fixed structural domains D and expand the shape-optimization problem from to D. Therefore, topology optimization can be generally formulated as follows:

$$\underset{\Omega}{inf}\ F = \int_D f\left(x, u\right) \chi\left(x\right) d\Omega \tag{6}$$

where χ represents a characteristic function which value is 1 if the area is in D, and 0 if not as follows:

$$\chi(x) = \begin{cases} 1 & if\ \forall x \in \Omega \\ 0 & if\ \forall x \in D \backslash \Omega \end{cases} \tag{7}$$

We designed a personalized stabilizer on Grasshopper using add-on *ameba*, developed for 3D topology optimization. *Ameba* is based on the bi-directional evolutionary structural optimization (BESO) technology. Bi-directional evolutionary structural optimization [12,18] is a finite-element method based on topology optimization, and is significantly more efficient than evolutionary structural

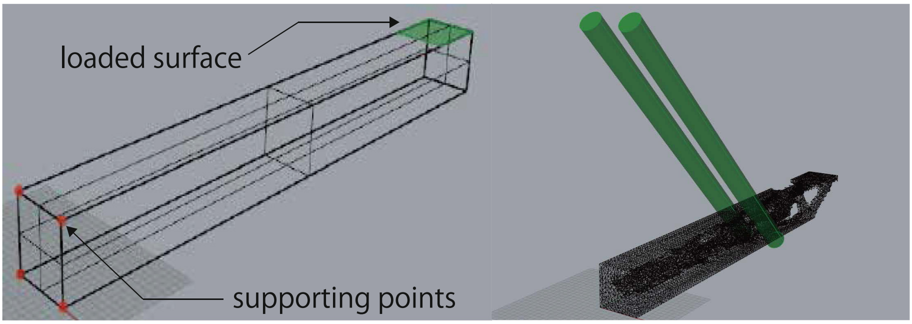

Fig. 8. System on grasshopper. Left: The supporting points is a red dot, and the green surface is loaded to the Z-axis negative direction. Right: The result model and two supporting poles. (Color figure online)

optimization [17] in terms of material removal. First, we defined the basic shape of a stabilizer prior to optimization, and both the points to support and the surface on which the load was placed as shown in Fig. 8 left. It is noteworthy that we allowed the users to hold the steering with both hands in this case to improve operability although Exo-Balancer used both shoulders as a fulcrum (see Fig. 8 right). Figure 9 right shows the Python component of the Exo-Balancer algorithm. The input values to the component consist of camera mass (c_mass), weight of the overall instrument (m_mass), length of user fuselage (bLength_n), and length between their abdomen and the position (mLength_L). According to the algorithm, calculation was conducted for the component. Subsequently, outputs from the component was used for the size optimization of a fundamental stabilizer. Finally, we conducted topology optimization for the shape optimization of a stabilizer. It is noteworthy that loads corresponding to a camera was applied to the Z-axis negative direction as shown in Fig. 8 right, the green surface. All parameters including the load for optimization are shown in Fig. 9 left.

The result is shown in Fig. 8 right. It can be exported as STL or OBJ file for 3D-printing. The shape transition for each iteration is shown in Fig. 10.

Pitch Directional Stabilization for Compact Camera. In this paragraph, we describe the structure that enables pitch directional stabilization as the first approach to address *issue3*. When a photographer moves in a certain direction, maintaining the equilibrium according to the direction by his/her own weight stabilizes the pitch direction. Some patents to explore and develop the method have been pended and granted. In particular, we focus on the patent pended by Da-Jiang Innovations Science and Technology Co., Ltd. (DJI)[6]. They filed many patents and invented a connecting device and a gimbal apparatus [9]. Following their idea, we attempted to generate a 3D-printable camera mount on which the structure for stabilization was installed. We designed it on Fusion360,

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[6] https://www.dji.com (Last accessed: 2019-02-15).

Camera mass	Stabilizer mass	n	L
400g	480g	48cm	43cm

Fig. 9. Left: Fundamental parameters. Right: we input these parameters into the Python component. Exo-Balancer algorithm is implemented in that component.

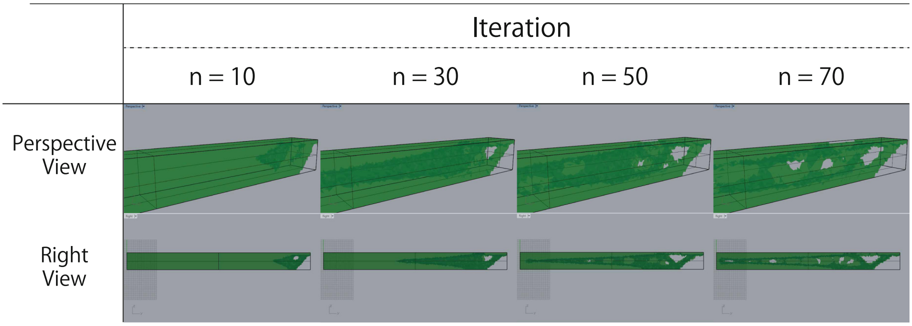

Fig. 10. Results through each iteration.

a notable 3D computer-aided design software. Figure 11 shows the output through MakerBot Replicator. Our proposed model was divided into two, and we used a commercial bearing to connect with these parts.

5 Discussion and Limitations

In this section, we firstly summarize our implementation, and then discuss some limitations and future work.

We chose topology optimization for shape-optimization to realize the personalized stabilizer without altering the shape of fundamental stabilizer. Topology optimization for the structure we define in Fig. 9(a) can be limited when applied loads to supporting or load-bearing positions within the structure. In other words, it is desirable that these structures corresponding to user's physical characteristics. Therefore, we need to have several basic structures, and then we use the different one depending on each user. We will also attempt to develop the system with automatic parameter tweaking functions for designing personalized stabilizer. It is generally known that not only the topology optimization but also almost all shape-optimized models are often coarse and not practical. Therefore, it is necessary to smoothen such coarse parts on a model. Laplacian smoothing algorithm [3] is one of the algorithms to smoothen a polygonal mesh.

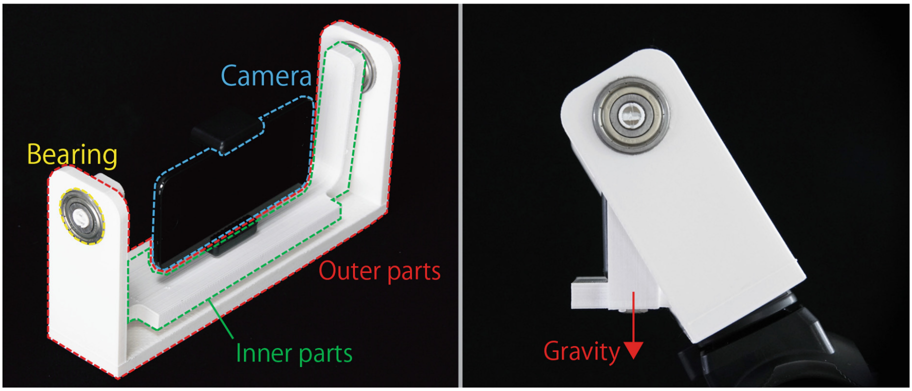

Fig. 11. Concept image of the structure which realize the pitch directional stabilization for compact camera. These parts unite into one by using a commercial bearing.

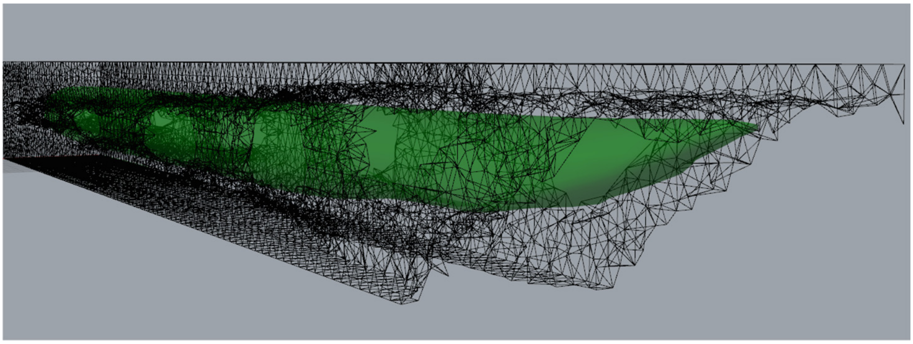

Fig. 12. Wireframes show the meshes of 3D model on which we conducted topology optimization, and its inside 3D model shows the one after laplacian smoothing.

According to the common recognition, we also smoothed our model. However, we tend to have more non-manifold edges in our models, therefore we could not conduct the process smoothly as shown in Fig. 12. More practical design will require more strict smoothing process based on Laplacian algorithm.

We developed a camera mount for pitch directional stabilization, and it is used for compact camera. However, it does not function when you use a camera with heavy lens because the center of gravity shifts remarkably.

Our future work requires practical experiments for various shooting situations. We conducted the shooting experiment in advance, in which a photographer stood still while a target object was moving. On the contrary, we can consider a shooting situation in which only the photographer moves while the target object is stationary, such as capturing a picture in the same pose or scanning a static object with a 3D scanner. Both the photographer and target object are stationary in the shooting situation, such as when photographing a landscape, and vice versa, such as when photographing a running athlete. Thus, several shooting situations exist, and must recruit specific participants such that their photographic skills can be divided into three ranks: professional, semi-professional, and novices. We will be able to gain more useful results through such a type of comprehensive user study.

6 Conclusion

Herein, we first reported the experimental results of Exo-Balancer, the first study pertaining to the design method of a personalized stabilizer, and subsequently presented the design method of a personalized stabilizer by topology optimization. Our primary contribution was to design personalized stabilizers through topology optimization method to establish ant end-to-end design framework that removed materials efficiently and render stabilizers 3D-printable. As a sub-contribution, we designed a fundamental structure for the pitch directional stabilization of compact devices on which a camera was installed such as smartphones. A comprehensive user study of camera users having different photographic skills in several shooting situations will be performed in the future. In addition, we will compare our method to conventional photographic methods such as commercial stabilizers or hand-held camera photography.

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