poimo: Portable and Inflatable Mobility Devices Customizable for Personal Physical Characteristics

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ABSTRACT

Despite the recent growth in popularity of personal mobility devices (*e.g.*, e-scooters and e-skateboards), they still suffer from limited safety and narrow design form factors, due to their rigid structures. On the other hand, inflatable interfaces studied in human-computer interaction can achieve large volume change by simple inflation/deflation. Inflatable structure also offers soft and safe interaction owing to material compliance and diverse fabrication methods that lead to a wide range of forms and aesthetics. In this paper, we propose poimo, a new family of PORTable and Inflatable MOBility devices, which consists of inflatable frames, inflatable wheels, and inflatable steering mechanisms made of a mass-manufacturable material called drop-stitch fabric. First, we defined the basic material properties of a drop-stitch inflatable structure that is sufficiently strong to carry a person while simultaneously allowing soft deformation and deflation for storage and portability. We then implemented an interactive design system that can scan the user's desired riding posture to generate a customized personal mobility device and can add the user's shape and color preferences. To demonstrate the custom-design capability and mobility, we designed several 3D models using our system and built physical samples for two basic templates: a motorcycle and a wheelchair. Finally, we conducted an online user study to examine the usability of the design system and share lessons learned for further improvements in the design and fabrication of poimo.

Author Keywords

Personal mobility devices; soft robotics; inflatable interfaces; shape-changing interfaces; graphical user interfaces design.

CCS Concepts

•Human-centered computing → Interaction design; User studies; •Applied computing → Transportation;

*The first two authors contributed equally to this work.

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UIST '20, October 20–23, 2020, Virtual Event, USA

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ACM ISBN 978-1-4503-7514-6/20/10 ...\$15.00.

<http://dx.doi.org/10.1145/3379337.3415894>

Figure 1. A: Electric motorcycle as an example of the inflatable mobility device. B: Parametric design software generates a tailor-made device by capturing the user's posture. C: The system supports wheelchair-shaped devices as well as motorcycle-shaped devices. D: Fabricated devices are lightweight and can be flattened after deflation for storage.

INTRODUCTION

Mobility is becoming personalized over time. Currently, our society depends largely on automobiles that allow individuals and groups to move around, commute, and transport cargo across long distances with little physical labor. However, we have recently seen increasing examples of slower but more compact motorized personal mobility devices (PMDs) such as e-scooters and e-skateboards [8]. These typically afford solo riders the capability of short-distance travel (*e.g.*, the last one mile from a station to the destination).

Despite the proliferation of PMDs, however, there are still three large design issues to improve: (1) most of the current mobility devices are bulky and heavy, resulting in limited portability and storage. We envision that the ideal PMD will be sufficiently small and lightweight to be stored in a pocket or a backpack when not in use. (2) They mainly consist of many rigid components and offer little safety in collision with pedestrians. (3) PMDs have limited design and form factor variability. Many design parameters are determined in advance by the manufacturer, typically allowing few (or no) customization options for users.

As a potential solution to these issues, inflatable interfaces [29, 5, 25], which are growing in popularity in human-computer interaction (HCI) and soft robotics, demonstrate potential ability, such as (1) large volume change from compact scale to room scale by inflation and deflation [22, 18, 23, 11, 21]; (2) soft and safe physical/emotional interactions [26, 7, 24]; and (3) custom fabrication resulting in diverse form factors [13, 14, 18, 28, 9, 12]. Our motivation is to leverage these properties of inflatable interfaces to improve current PMD designs.

In this paper, we present a new family of PORTable and In-flatable MOBility devices called poimo, which consists of inflatable frames, inflatable wheels, and inflatable steering mechanisms (Figure 1). First, we defined the basic material properties and mechanics of inflatable structures that can be strong enough to carry a person, while simultaneously allowing for soft deformations. We also implemented an interactive design system that can scan the user's desired riding posture and preferences to generate a custom shape and color. To demonstrate the mobility and design capability of poimo, we prepared two basic template structures: a motorcycle and a wheelchair. Finally, we conducted an online user study to examine the usability of the design system and share lessons learned for further improvements in the design and fabrication of poimo.

The main contributions of our paper are listed below.

1. We proposed two example forms of poimo that leverage soft and inflatable bodies for novel interaction opportunities such as storage, portability, and safety
2. We identified material construction methods and physical structures of poimo that can function as a vehicle while allowing for reversible shape change via inflation and deflation
3. We provided a scan-based design system that allows users to design and customize poimo for their needs and tastes
4. We performed an online-based user study and reporting feedback about the usability of the poimo design system

RELATED WORKS

Vehicles in HCI

Many recent studies on vehicles in HCI focus on human-vehicle interaction [15], including driver-vehicle interaction [3, 6] and pedestrian-vehicle interaction [1, 16]. Among these, Eguchi *et al.* prototyped an autonomous vehicle having soft and inflatable exterior that could notify a pedestrian of which

driving mode (*i.e.*, manual or autonomous) was being used, by changing the body shape [4]. Although this prior work shared the concept of inflatable mobility, their motivation was only to augment standard autonomous vehicles with a visual notification system. We instead aim to replace most of the vehicle itself with inflatable materials, and thereby introduce a new type of mobility vehicle together with the compact, safe, and easy-to-customize capabilities enabled by inflatable interfaces.

Inflatables Pneumatic Interfaces

In HCI, inflatable pneumatic interfaces first drew attention as devices that can render haptic sensation. For example, Harrison *et al.* [5] and Yao *et al.* [29] used pneumatic channels embedded inside silicone structures to implement VR tactile displays and shape-changing interfaces, respectively.

Another benefit of inflatable interfaces is their large volume expansion and contraction capabilities. Swaminathan *et al.* [22] and Murayama *et al.* [11] proposed methods of building room-scale objects that were easy to deploy and shrink on demand. In the field of soft robotics, Takeichi *et al.* [23] implemented a 20-m-long robotic arm using a foldable thin pneumatic structure.

Pneumatic interfaces are also used for physically and emotionally safe interactions with robots. For example, Whitney *et al.* [26] and Kim *et al.* [7] utilized silicone-based pneumatic robot arms to create physically gentle interactions with fragile objects and humans. Ubaldi *et al.* implemented an inflatable robot Puffy inspired by the film "Big Hero 6," which gave children a fluffy and warm impression of safety and care [24]. In other cases, some researchers leveraged soft and safe interaction of inflatables in wearable contexts [30, 27].

Finally, there are many HCI reports of fabrication methods for inflatable interfaces. Sticky Actuator [13] and aeroMorph [14] provided methods to design and implement diverse shapes of planar pneumatic actuators by heat-sealing plastic and fabric films, respectively. Liquid Pouch Motors [12] and milliMorph [9] extended planar actuators by filling the pouches with low boiling point liquid to thermally drive pneumatic actuation. Regarding 3D-shaped pneumatic actuators, Sareen *et al.* developed a fabrication method for furniture-scale inflatable objects by using thermally bonding creases on the film [18]. AccordionFab enabled the fabrication of inflatable 3D objects by laser cutting and laser welding multi-layered plastic sheets in one simple process [28].

We leveraged abovementioned characteristics of inflatable pneumatic interfaces, *i.e.*, large volume expansion and shrinkage, soft and safe interaction, and easy fabrication, to achieve poimo.

Interactive Design System

Some interactive design systems utilize 3D scanning or posture recognition to automatically input the objects' shape and human postures into the software. For example, Chen *et al.* proposed a design software that 3D printed custom adaptations of everyday tools to, for example, extend the arms of pliers to fit unique users [2]. In this procedure, the user first scans the tool and then measures the hand size to post-process the design

in software. In ElectroDermis [10], Markvicka and Wang *et al.* implemented a software tool to customize wearable electronic bandages that fit a 3D scanned body shape. Zoran *et al.* built a hand-held digital milling device that continuously tracked the position of the device tip and automatically extended or retracted the tip to help users sculpt a target 3D object [31].

In this paper, we followed these design methods to implement a scan-based design system that can optically capture the user's riding posture for a custom design of poimo.

PORTABLE AND INFLATABLE MOBILITY DEVICES

Here, we envision a new category of inclusive mobility devices that are uniquely tailored to many types of users' demands; also, they are safe, affordable, and lightweight, requiring little space for storage. Inflatable structures represent a key technology that can satisfy these conflicting demands. They allow us to construct and use vehicles on the human scale, as well as carry and store them when deflated. They can also be rigid and hold the human weight while remaining soft enough for comfort, safety, and transformation.

In Figure 2, we mapped potential applications of customizable and inflatable mobility devices in design space with autonomy on the x-axis and travel speed on the y-axis. We might be able to include not just PMDs but also public transportation in the scope of inflatable mobility devices. In addition to wheeled vehicles, poimo's design philosophy could potentially be applied to wearable devices as well as aquatic and aerial vehicles.

From this wide range of applications, we chose electric motorcycles (Figure 3A) and human-powered wheelchairs (Figure 3B) to demonstrate how our approach can inclusively aid human mobility and meet the user's unique requirements and preferences. Towards this goal, we demonstrate a few derivative mobility designs that can conform to the physical characteristics and preferences of the user. We also discuss our interactive software tools with which the users can interactively design their own devices.

Materials and Fabrication

Although inflatables provide an attractive construction method, there remain issues of strength and shape freedom. For example, vinyl inflatables such as pool floats lack structural durability. Polyvinyl chloride (PVC) fabrics used for inflatable boats are strong, but the basic shape is limited to tube-like structures. Instead, we adopted a unique composite material called drop-stitch fabric, also known as double-wall fabric. This fabric comprises two parallel surfaces connected by a web of long pile yarns (Figure 4). The approach using the drop-stitch fabric allows for the creation of flat and rigid inflatable boards; they are typically used for manufacturing stand up paddleboards (SUP). This inflatable structure is lighter for its size and strength, while also being soft to the touch. The standard thickness of drop-stitch fabrics is between 25 mm and 450 mm. We used a 200-mm-thick fabric for the body of the motorcycle, and a 150-mm-thick fabric for the wheels, forks/arms, and seats.

Figure 2. Potential applications of inflatable mobility devices.

Figure 3. A: Design examples of a motorcycle. B: Design example of a wheelchair. The isometric drawing displays the assembly of inflatable parts.

In our prior work [19], we built the body of an electric scooter using drop-stitch fabric. However, the entire structure was not fully constructed from inflatables. The wheels and the suspensions were made of rigid components. In this paper, we conducted further experiments to clarify the properties of drop-stitch inflatables and updated our design by adopting the wheels and suspensions out of inflatables structure.

The fabrication process of poimo is shown in Figure 4A. We send the pattern data to a factory and receive the finished product in about a week. The drop-stitch fabric, cut from a roll according to the desired pattern, becomes an airtight inflatable structure sealed by a valve (Figure 4B) and a sidewall (Figure 4C). The valve is the same one used for commercial inflatable boats and SUPs, and the pump is widely available for purchase. Additionally, there are surface fasteners to connect different inflatable components together. Metal plates with threaded holes are also glued to it to mount the bearings, shafts, casters, and handles.

We note that conventional vehicle frames are made by welding, die casting, and sheet metal stamping. Compared with this process, the production of inflatable components is easier and less expensive, and the lead time is far shorter.

Figure 4. A: Fabrication process of the drop-stitch inflatables. From left to right, we cut pattern shapes from the raw fabric roll and adhere side walls to the edges of the cut fabric. Additional valves, metal mounts, surface fasteners, etc., are glued. B: A valve on the wheel. C: Drop-stitch inflatable with a transparent side wall to show the pile yarns.

Wheels, Steering, and Riding Comfort

Although the design and fabrication of inflatables have already been investigated for complex 3D models [20], furniture [18], and architecture [11], there have been no reports about the fabrication and discussion of inflatable wheels/steering and their ride quality, all of which are unique to mobility devices. Here, we show how these novel elements can be achieved using drop-stitch inflatables.

Inflatable wheels

There is a trade-off between the size of the wheels and the ride quality. Wheels having a relatively small diameter (e.g., collapsible electric scooters) are typically disadvantageous in terms of their ability to handle bumps in the road. On the other hand, larger wheels offer a smoother ride but are heavy and inconvenient to carry around.

As a breakthrough, we developed a novel wheel with inflatables by directly attaching a wheel hub to a disc-shaped drop-stitch inflatable structure. Owing to the fabrication process of the drop-stitch fabric, these circular inflatables are easy to customize at different diameters. This inflatable wheel inherently has the smoothing function of a pneumatic tire, but it can also be rolled up and folded for storage, unlike standard rigid wheels.

Steering mechanism

Although the strength of the drop-stitch fabric is beneficial when transporting and sustaining the human weight, its stiffness can be disadvantageous when we try to bend it to steer the wheel. The challenge is to create a hinge for the steering mechanism without using any rigid parts. Thus, we proposed a method to fabricate an integrated hinge by partially narrowing the width of the inflatable board using a linear seam (Figure 5A). We note that a similar approach exists for the articulated structure of an inflatable robot [17].

In case of the motorcycle, steering characteristics vary depending on a *trail* parameter. As shown in Figure 5B, the trail is

Figure 5. A: Hinge structure for steering. B: Positive trail signifies stable steering response. Zero trail provides agile steering.

the distance between the point of ground contact of the wheel and the point where the hinge axis meets the ground. The trail value is determined by both the hinge position and the angle of the front fork. When the trail value is positive, a restoring force acts on the front wheels, causing them to straighten. Thus, by appropriately choosing the amount of trail, users can choose the steering characteristics of stability and agility.

Riding comfort on inflatable bodies

The inflatable body works as a suspension without swing arm mechanisms or additional springs, owing to the natural compressibility of air.

To examine the riding comfort of the inflatable body, we performed a loading test by applying a weight to the drop-stitch fabric, as shown in Figure 6A. We built a device to hold an inflatable board vertically over a force gauge. The board was supported at two points by small rollers attached to the end of the support structure, and force was applied via a pipe with a large diameter at the center. During measurement, we started from a no-load state and gradually applied a quasi-static load up to 800 N (~ 82 kg), which is the target load capacity. Then we returned to the no-load state. The inflatable board was 1000 mm in width, 450 mm in height, and 150 mm in thickness.

Figure 6B shows the relationship between the displacement and the load for two different pressure conditions: 58.6 kPa and 24.1 kPa. As a result, the inflatable board sustained a load up to 800 N. Additionally, the relationship between the load and the displacement suggests that the body works as an adjustable spring by which the users can choose an appropriate riding quality. For example, by increasing the internal pressure, we can increase the natural frequency, which is related to riding comfort. Unlike traditional vinyl balloons, drop-stitch inflatables can tolerate large internal pressures. Thus, they are uniquely suitable for vehicles.

Figure 6. A: Experimental setup for the loading test. B: Load-displacement property of the drop-stitch inflatable boards for different inner pressures.

Speed of inflation

In our prior work [19], we reported that the time required to inflate a drop-stitch sample with a rectangular shape (600 mm in length, 1150 mm in width, 150 mm in thickness, and approximately 0.1 m³ in volume) to the fully inflated state (41.4 kPa) was approximately 71 s when using a hand-held 20 PSI pneumatic inflator (THE SHARK, OutdoorMaster Inc.). We regard this inflation speed as reasonable for many use scenarios, for example, inflation at a station or a bus stop.

Electric drive system

Our proposed mobility devices allow both manual and electric driving power. Electric vehicles such as motorcycles use a brushless motor that is pressed against the wheels to transmit torque through frictional force instead of using gears or belts (Figure 7). The motor is located between the top of the rear wheel of the motorcycle and the body.

By using an inflatable structure, the weight of the motorcycle is roughly one-tenth of the rigid body bikes on the market. This weight is comparable to an e-scooter, while maintaining the look and feel of a regular motorcycle. To start driving from the stopped state, the torque that overcomes the inertia of the bike itself is small enough to be ignored, and the load (*i.e.*, the weight of the rider) becomes dominant.

We adopted a commercialized brushless motor typically used for electric skateboards as shown in Figure 7 right. The controller communicates wirelessly with the control box connected to the motor, which includes a motor driver circuit and a rechargeable battery. The control box was mounted on the side of the body near the motor. The controller allows for motor speed adjustment, electromagnetic braking, and switch going directions.

Figure 7. Electric drive system for the motorcycle-shaped poimo.

Figure 8. Height-adjustable supports: a handrail, a stool, and footrests for scanning.

INTERACTIVE DESIGN SYSTEM

In the previous section, we explained the mechanical properties of poimo as a pneumatic mobility device. In this section, we will introduce the interactive design system by which users can visually and parametrically design their own mobility devices depending on their physical characteristics, use cases, and tastes.

Overview

Our interactive design system largely consists of two processes: the scanning process to get the user's physical characteristics and the designing process to customize the mobility on the graphical design software interface (Figure 1B). Because dealing with a user's individual body characteristics is an important and unique factor to design an inclusive and personal mobility device, we combine the scanning process and the following parametric design process, rather than just completing all the processes on the computer.

A user first selects a template (*i.e.*, motorcycle or wheelchair). In the template, the basic shape of the vehicle, the number of parts, and their positions are predetermined. Then, using an optical capturing device, they capture their riding posture as an input. The software automatically generates a baseline design depending on the input. Based on the suggested initial design, the user can adjust the design until satisfied. When finished, the user can export the completed design and place an order to the manufacturer of the inflatable structure.

Scanning Process

During the scanning process, the user first selects a vehicle template and provides a natural pose corresponding to the vehicle. The user can then adjust the supports (*e.g.*, stool, handrail, and footrests) to iteratively simulate a riding posture, as shown in Figure 8. The user can use the supports that already exist at home, or the manufacturer can provide some regularized set of supports. Once the users are ready, the system asks the user to hold the pose for five seconds while a

Figure 9. Screenshots of the design software and variations of the mobility devices for the posture. There are motorcycle and wheelchair modes.

Table 1. Design parameters and constraints for motorcycle.

Slider controls	Parameter descriptions
Front Fork Deg.	Angle of the steering hinge. This value also affects the position of the wheels.
Hand X, Y	Position of the handle.
Seat Height	Height of the seat. The seat position is lower than the handle by a certain value. This value also affects the diameter of the wheels.
Wheel Size	Diameter of the wheels. The diameter is constrained to fit under the seat.
Body Bottom	Ground clearance between the ground and the vehicle body.
Trail Offset	Amount of the trail. This value also affects the position of the hinge.

Microsoft Kinect v2 captures their posture and measures their skeletal structure.

Automatic Generation of Baseline Design

Based on the skeletal data gained from the users' posture, the software automatically generates the baseline design, as shown in Figure 9 left. This initial design can be transformed parametrically in the post process, but the basic shape, thickness, and the number of each component remain unchanged. Here, we describe the automatic generation process of each vehicle.

Motorcycles

First, the software calculates the center of gravity (CoG) of the user's body. Based on this CoG, the position of the seat is chosen so that the distance between the front and rear wheels from the center of gravity will be in the ratio of 2:1. Also, the seat height (see Table 1) is decided based on the position of the user's waist. Likewise, the position of the handlebar (*i.e.*,

Table 2. Design parameters and constraints for wheelchair.

Slider controls	Parameter descriptions
Seat Height	Height of the seat.
Wheel Size	Diameter of the wheels. The diameter is constrained so that the axle position will fit under the seat.
Seat Depth	Depth of the seat.
Backrest Height	Height of the back from the seating face.
Wheel Offset	Wheel axle position in the front and rear directions.
Nose	The amount of protrusion of the middle board of the seat.

Hand X and Hand Y in Table 1) is fixed at the position of the user's hands. All the other parameters in Table 1) are set to default values.

Wheelchairs

As with the motorcycles example, the seat height (see Table 2) is the first decision based on the position of the user's waist. Then, based on the position of the user's hands, the position of the wheel center (*i.e.*, Wheel Offset in Table 2) and the diameter of the wheel (*i.e.*, Wheel Size in Table 2) are decided. All the other parameters in Table 2) are set to default values.

Designing Process

Next, the users can modify the automatically generated vehicle design by changing the parameters using the sliders on the left of the user interfaces (Figure 9). Adjustable parameters are listed in Table 1 (for the motorcycles) and Table 2 (for the wheelchair). We note that the width of narrow components is initially set to a certain minimum value to guarantee strength,

Figure 10. A series of snapshots of the test ride: a motor cycle model (above) and a wheelchair model (below).

but the user can increase the thickness later. The user can also choose the color of each body component using the color pallet. The software allows to rotate the 3D model, and all the parametric modifications by the user are reflected in real time.

Here, for example, let us assume that a user likes a riding experience similar to the touring motorcycle. Then, the user can increase the Trail Offset value, which contributes to a steady and straight runs at faster speeds. When a user wants more of a city cycle, the user can decrease the Trail Offset value, which is suitable for frequent turns at lower speeds.

As another example, a wheelchair user who likes sports (*e.g.*, race on the track) might prefer a forward-leaning posture. Then, the user can increase the value of the Nose to put the forward wheel farther from the seat to balance the posture.

Likewise, the users can iteratively try parameters by checking the vehicle model and the skeleton until they feel satisfied.

Order and Assembly

Following the designing process, the user can export the completed 3D design data by pressing the “Export” button. The generated model data include the scale and color information that is used to place an order to the manufacture.

After the order, the completed poimo will be shipped from the manufacturer to the user in a compact deflated form, as shown in Figure 1D. The users can complete the construction by inflating each part and assembling the pieces. Assembly is a simple process of aligning the surface fasteners attached to components and tightening a few screws to support the bearings. For inflation and deflation, the user can either use a manual pump or a commercially available electric pump to save effort. In both cases, they can typically check the air pressure by the pressure gauge installed to them.

RIDE EXPERIENCE

In this paper, we physically implemented and tested two variations of motorcycles and two variations of wheelchairs. Samples are shown in Figure 11A and 1C. With all versions, we verified that we were able to deploy, ride, and fold the vehicles in our pilot test (Figure 10).

Electric Motorcycle

The body has rounded edges and is 200-mm wide, allowing it to work well as a seat. The softness of the inflatable structure provided a slightly bouncy ride. During the launch, the lack of stability around the roll axis at a low speed required us to kick the ground to gain initial velocity. Once the speed got higher at around 10 km, however, the ride became stable and we were able to go straight without big fluctuation on a level and smooth road surface. The minimum turning radius of the poimo motorcycle with a wheel diameter of 400 mm and a wheelbase (the distance between two wheels) of 900 mm was about 3 m. This is about twice the value of a similarly sized, commercially available rigid motorcycle. The reason for this increased turning radius is that the front forks and rear swing arms are thick and easily scratches with the ground when the vehicle is tilted.

Wheelchair

The serially connected components form a wide seat that can stably support our posture. For simplicity, there were no hand rims (push rims) on the rear wheels, but the wheels were large enough to allow the wheelchair to be firmly propelled by hand. A gap between the rear wheels and the body was necessary, because the load causes the rear wheels to tilt and produce a camber angle. The stiffness of the cantilevered wheels was the main reason for the limited load capacity.

USER STUDY

Overview

We performed a preliminary user study to obtain initial design feedback for our design software and the construction process. Our user study consisted of six participants (five males and one female) in their twenties, none of whom had any experience in product development using soft materials. In the user study, participants watched a video showing the design and assembly process of both types of poimo using the interactive design system. Participants were then asked to evaluate their expected experience of poimo customization and assembly.

We canceled the physical user study of both the riding and the design experience to ensure appropriate social distancing, due

to the COVID-19 pandemic. The entire process of this user study was conducted online.

Process

This user study was conducted using the online conferencing system, ZOOM, through the following process:

1. Participants watched an approximately 9-min-long video that showed the design process of two types of poimo: motorcycle and wheelchair. The following three steps were demonstrated:
 - (1) The scanning process of the user's posture.
 - (2) The designing process by changing the parameters on the interactive design software.
 - (3) Assembly of the manufactured poimo components.
2. Participants filled out a questionnaire about the content of the video.
3. We conducted semi-structured interviews related to the questionnaire.

The questionnaire consisted of three sections (On the usability of the interactive design software / On the usability of the assembly of poimo / On the utility of the interactive design software and poimo) with 12 questions in total as shown Table 3. The answers were rated on a 5-point scale (1. "No. not at all," 3. "Neither," 5. "Yes. very much") by participants. For all the scores from participants, please refer to our supplementary information.

Result

Based on the questionnaire in Table 3 and the interview results, we summarized the perceived usability of poimo from three perspectives: (1) the usability of the interactive design software, (2) the usability of the assembly of poimo, and (3) the overall utility of the interactive design system and poimo. We also shared the feedback gained from the semi-structured interviews and classified them for discussion and future improvements.

On the usability of the interactive design software

Most participants rated the usability of the software interface high, with an average score of 4.5 out of 5 points. To intuitively design diverse shapes by adjusting individual parameters, the information design of the interface and the real-time generation of 3D models based on parameters were found to be highly useful for this purpose (P1: "I thought I could find a shape I liked when the video was showing the various models with different parameters." in response to Q3).

Although usability and the familiarity of the interface were rated high, some participants reported a lack of uniqueness in the interface (P1: "The interface doesn't feel new, but I think it's a reasonable choice" in response to Q1). Furthermore, one user pointed out that some parameters essential to adjust the riding quality of poimo were missing (P4: "As for the wheelchair, it would be nicer if it had a parameter to control the backrest angle." in response to Q2, and P6: "I think the parameters except for the shape and the color were not considered in the software." in response to Q3). We also recognized the issue that the user could not well grasp the dependency

Table 3. Survey questions

On the usability of the interactive design software

Questions

- Q1. Do you think this software is intuitive?
 Q2. Do you think you can find the parameters needed to create a mobility you expect?
 Q3. Does the shape generated as a result of the adjustments by parameters correctly reflect your design intent?
 Q4. Does the software interface match your preference?

Answer

1.No. not at all - 3. Neither - 5.Yes. very much

On the usability of the assembly of poimo

Questions

- Q5. Do you think the completed components are the proper size and shape to assemble?
 Q6. Can you assemble this mobility without any mistakes?
 Q7. Does the complete poimo meet your expectations compared to what you were seeing in the software?
 Q8. Do you think you were able to design poimo that suits your body without any stress?

Answer

1.No. not at all - 3. Neither - 5.Yes. very much

On the utility of the interactive design software and poimo

Questions

- Q9. Is this software going to help you create poimo that you expect?
 Q10. Do you have any concerns about poimo made of soft materials?
 Q11. Do you think poimo will be useful in your life?
 Q12. Do you want to use this interactive design system to create poimo?

Answer

1.No. not at all - 3. Neither - 5.Yes. very much

between different sliders. In the current implementation, when the user changes the value of one slider, it can affect the values of other sliders (P1: "Regarding an inevitable change of one parameter corresponding to others, some users could not clearly understand the dependency of each parameter. If I were a user, I might become interested in the correlation between the parameters." in response to Q2).

On the usability of the assembly of poimo

Regarding the appearance of the poimo, many participants responded that there was almost no difference between what they had designed in the software and the actual poimo. Many participants also said that the poimo seemed easy to assemble without any mistake (P5: "I felt I could assemble it even if there were no instructions." in response to Q6).

On the other hand, some participants were concerned about the lack of information in the software to check the rigidity and the haptic feel of the poimo when they actually touch it. One participant noticed a difference between the color shown on the interface without any background image and the actual body color of the completed poimo in the real environment (P4: "The colors seem to be difficult to reproduce in the software. I wonder if users feel the gap because they can't see it in the actual environmental background where they will use it." in response to Q7).

On the utility of the interactive design software and poimo

According to the answers to Q12, all the participants agreed that the interactive design system was useful. However, two participants felt neutral to Q11 on the utility of the poimo itself. They mentioned that they still had no idea how poimo would be used in real life because they did not see an actual sample of poimo.

Furthermore, some participants expressed concerns about using a soft material during a driving, considering their anxiety about safety, performance, and legal requirements for the practical use of poimo (P6: *“I don’t think soft mobility is going to kill a person even if I ride on it and hit someone, but I don’t think it’s practical to drive on a driveway. Bicycle lanes should be better for it for the city ride.”* in response to Q10).

Suggestions for further improvements

Inspired by the poimo vehicles which are made of soft materials and thereby not yet commercially available, the participants provided many positive comments and ideas for improvements. The given suggestions were classified into the following five main categories:

1. More intuitive software: the corresponding and changing parts of the model should be highlighted when the user adjusts parameters; common shapes and colors should be made available as preset patterns (e.g., “ape handlebar” motorcycle).
2. The physical feeling of the poimo before shipping: participants wanted to know the expected weight, texture, rigidity, color, and size of the components in the software before they receive the actual poimo.
3. Improved customizability: participants suggested to add optional components, such as a roof and a basket. One participant wanted to print his favorite photos and patterns on the body of the poimo, rather than painting it with a single color. As well as the customization of poimo on the software interface, another participant proposed physically deforming the completed poimo to modify the form factor, by taking advantage of its soft material properties.
4. Simplification of posture measurement: instead of using Kinect to measure the users’ posture, some participants proposed a measurement method that only requires a smartphone camera to lower the barrier of installing special device for the scanning process.
5. Assembly instruction: many participants expected an assembly instruction manual would be helpful. Specifically, they proposed to attach a process diagram and an exploded view in a manual, and to print guides on the surface of the poimo to help with assembly.

LIMITATION AND FUTURE WORK**User Study of the Riding Experience**

In this paper, we could not complete the user study regarding the riding experience due to COVID-19. However, we believe that it is extremely important to obtain feedback on human factors when using and riding the actual poimo motorcycle and wheelchair in a future study.

Traveling Performance

Our poimo vehicles can run on the flat and smooth surfaces. However, we have not yet conducted a long-term and long-distance driving test. In the short-run test of the poimo motorcycle, we occasionally observed the vertical bouncing of the driver even on a flat course. This could be a resonance factor caused by the elasticity of the wheel and body that are not properly adjusted by the internal pressure. Additionally, because the poimo is lighter than normal vehicles and has a higher center of gravity position, a new analysis of driving stability is required. As a side note, when the poimo was parked outdoors, it moved in the wind.

Availability and Price of Drop-Stitch Fabrics

One of the limitations of the poimo is that the production of drop-stitch inflatables is currently difficult to achieve at home or in a lab. In this study, the fabrication of three motorcycles (including one prototype) and two wheelchairs was outsourced to a manufacturer. The price was approximately \$1,500 per vehicle. Unfortunately, there are no accessible digital fabrication tools (e.g., a laser cutter or a 3D printer) so far. It would be beneficial to develop a new digital fabrication method for drop-stitch fabrics to reduce the cost and the lead time.

Design Freedom of Inflatable Structure

The design system proposed in this paper ensured the merit of limiting the shapes of poimo to the templates. On the other hand, an alternative approach would include free-form modeling, which would allow users to sketch and “knead” the shape of the model to modify the structure as desired. However, vehicles would have severe design constraints, and thus we need to carefully decide the region where free modeling is (or is not) allowed.

As another limitation, the inflation time of the poimo vehicle linearly increases with the volume. Additionally, as the number of components increases, we need to inflate each of them separately. Thus, when designing a new shape of poimo, we should consider the balance among function, aesthetics, and effort of inflation.

Finally, the edge of the inflatable structure is inevitably rounded in the current design, which may affect the physical and the psychological impression. A new technology to more freely control the shape of inflatable structure is left for future work.

Interaction with Internal Pressure Sensing

Our current implementations require close contact with users. Thus, leveraging such contact presents interesting opportunities as future work. Because drop-stitch inflatables are the structures supported by internal air pressure, it is possible to detect deformations by measuring change in the pressure, as partially accomplished by [22]. We expect that riding posture estimation allows direction control based on body movements.

CONCLUSION

The focus of this paper was to radically change the structure and the user experience of personal mobility devices. We proposed poimo, a new family of portable and inflatable mobility devices. We successfully implemented and presented

inflatable and deflatable motorcycle- and wheelchair-shaped mobility devices for the first time, to the best of our knowledge. We provided a user-friendly tool with which users can interactively design vehicles to suit their unique physical characteristics and preferences. We conducted an online user study based on the survey and semi-structured interview. From the results, we observed the participants' interest in poimo and thereby room for social acceptance of these novel types of personal mobility devices.

We believe that this paper will give a totally new viewpoint of how we fabricate and interact with mobility and how we use personal mobility devices as well as other mobility devices and public transportation. This study on inflatable personal mobility devices is only the beginning, and we expect further participation and exploration.

ACKNOWLEDGMENTS

This work was supported by JST ERATO Grant Number JPM-JER1501 and Mercari Inc., Japan. We acknowledge Airbox Co., Ltd., Korea for fabrication support of the drop stitch prototypes, and Dr. Jie Qi for helpful comments.

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