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Modular Haptic Feedback for Rapid Prototyping of Tactile Displays

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Abstract— **This work presents the foundations of a novel haptic toolkit, consisting of a set of modules that seeks to enable designers to easily and quickly produce new tactile prototypes. The modules are re-attachable, wearable, wireless, customizable, and can be placed on different parts of the body. This paper first discusses a series of design decisions that were made when producing these modules. The paper then presents a set of five modules that were created using the decided upon design techniques. The five haptic modules presented produce the three most common tactile feedback modalities: vibrotactile, skin-stretch, and probing. Each module haptic cue parameters can be customized and controlled wirelessly through an off-board computer. The modules can be used either in isolation or in groups for haptic sketching to rapidly iterate through tactile displays.**

I. Introduction

Haptic feedback has become an increasingly popular approach to connect humans to technologies. For example, modern smartphones can generate expressive vibration cues and haptic steering wheels can keep drivers safe. Haptic technologies can also help connect people with each other by allowing them to exchange and share touch sensations over a distance [1]. However, there are still many obstacles that designers must face when creating new haptic experiences [2]. Significant effort is required to develop the hardware and software necessary to design a haptic experience, thus making it expensive, in terms of time and money, to iterate through designs. Furthermore, few people have the prerequisite skill set to create new haptic experiences, and it can be difficult to include persons with varying life experiences and domain expertise as full partners in the design process. Therefore, there is a need for haptic toolkits that allow the user to easily customize and combine different haptic sensations to enable both novice and expert designers to easily and quickly prototype haptic experiences.

In this paper, we first created design methods that can be used to build self-contained tactile modules that will allow haptic designers to customize and combine haptic cues to rapidly iterate through haptic sketches until a desired sensation is achieved. We present haptic modules which are designed to be easily attachable and detachable and can be used on almost any part of the body, giving haptic designers the ability to stimulate less explored areas of the body such as the legs or the neck. We created five modules, shown in Fig. 1, that elicit the most commonly used tactile modalities, namely, vibrotactile, skin-stretch, and probing. We envision that these novel haptic modules will enable users to easily and rapidly design new haptic experiences, which will not only help generate faster prototypes, but will also invite potential end-users to participate in all stages of the design process.

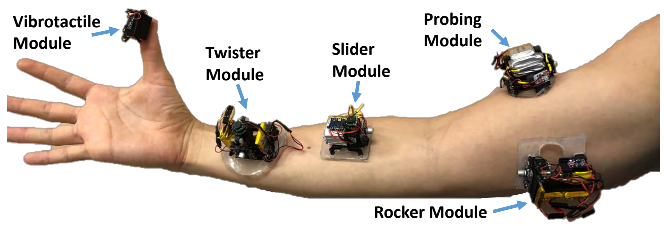

Fig. 1. A user's arm with five self-contained re-attachable haptic modules.

The rest of the paper is outlined as follows. In Section II, we describe previous efforts to reduce barriers when creating novel haptic designs. Design choices related to the skin-safe adhesive, methods to allow the modules to conform to the body's curvature, and power and communication are discussed in Section III. In section IV-A, we discuss the vibrotactile feedback module. The different skin-stretch haptic modules are described in section IV-B. The probing module is explained in section IV-C. Section V explores how the modules could be used to create haptic sketches. Lastly, Section VI outlines future work.

II. Background

To reduce the aforementioned design barriers, several researchers have created toolkits to enable rapid iteration of haptic experiences generated by existing haptic hardware. Some toolkits enable end-users to generate haptic effects by applying a library of pre-existing haptic cues, e.g. [3], [4]. Other toolkits allow users to record physical interactions, and either replay these interactions, e.g. [5], [6], or render similar interactions, e.g. [7], [8]. Educational toolkits, such as the Hapkit, teach students how to program haptic experiences using traditional coding techniques [9], [10]. Toolkits may also give users the ability to generate new haptic experiences through the use of graphical user interfaces, which allow a user to intuitively explore possible haptic cues and patterns generated by some hardware [11], [12].

Few efforts have been made to enable users to quickly iterate over the hardware used in haptic devices. Designer Camille Moussette introduced the concept of haptic sketching [13]. Just as quick sketches can help designers rapidly

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iterate through visual designs, haptic sketches are meant to help designers rapidly iterate through haptic designs. Moussette explores the idea of haptic sketching in several ways, including creating a series of handheld tactile modules whose haptic sensations could easily be changed through interchangeable mechanical pieces. He also ran a series of workshops on haptic sketching where novice participants created and programmed haptic devices out of common craft materials, such as hot glue and rubber bands, and simple actuators. He noted that the duration of the workshops, which lasted between 4 and 6 hours, did not seem sufficient for workshop participants. When participants started with raw materials and needed to write low-level code for new devices, he concluded that "quick, non-committal, and explorative constructions are generally not compatible with controlled actuation and repetitive movements" needed in haptic devices [13]. In another example, Park et al. created a set of vibrotactile units that can be attached and detached to objects, such as a laser pointer, to enable the object to produce vibrotactile sensations [14]. Designers may use these units to quickly prototype new tactile experiences for handheld objects.

Traditional fabrication methods for tactile displays, where haptic actuators are embedded in a wearable object, such as a garment or brace, or an object that makes contact with the skin, such as a chair, make it difficult for users to rapidly iterate through tactile designs. For example, garments are meant to be used for a specific body part, so it would not be possible to use a device meant for the arm or leg on a body part with significantly different curvature, such as the neck. Cutting edge soft-haptic devices, e.g. [15], and skin-integrated haptic devices, e.g. [16], can be readily placed on areas of the body with complex curvature. However, many of these devices require external actuation systems or fabrication methods that are not readily available.

III. Haptic Modules Design Decisions

Prior efforts towards enabling rapid prototyping of tactile displays have focused solely on vibrotactile cues generated by either a single vibrotactile actuator or an embedded array [12], [17], [18]. However, because the spacing between actuators can significantly affect the produced tactile sensation [19], we believe that it is important to enable users to easily adjust spacing between the actuators while creating their displays. For this reason, we sought to create re-attachable modules. This section describes design decisions made to create the re-attachable, wireless haptic modules.

Because vibrations traveling through the wires of wired modules can affect the performance of tactile displays [13], we decided to create fully self-contained modules. We also sought to design and create modules that deliver different tactile modalities to allow designers to create rich tactile sensations capable of accommodating varying user sensitivity requirements or preferences.

A. Skin-safe adhesive evaluation

Our goal was to find a reusable, skin-safe adhesive which could attach to any part of the body while supporting our haptic devices through any motion. To this end, we evaluated the following different tapes and adhesives for our devices:

1) Double-sided clothing and body tape (CLING IT2)
2) Electrocardiogram (ECG) tape (3M and Red Dot)
3) Double coated medical tape (3M, product no. 1522)
4) Medical non-woven tape (3M, product no. 9917)
5) Ecoflex Y (Ecoflex Gel with 20% Slacker, Smooth-On)
6) Ecoflex Z (Ecoflex Gel with 30% Slacker, Smooth-On)

Ecoflex Y and Z are adhesive gel pads fabricated by molding mixtures of Ecoflex Gel and Slacker (Smooth-on). Chossat et al. developed an elastomeric adhesive made from Ecoflex Gel and Slacker (Smooth-on) that could be reused indefinitely [15], however they did not describe the concentration of Slacker in their adhesive. Therefore, we experimented with various concentrations of Slacker, which affects the softness and tackiness of the silicone. Slacker concentrations $\leq$ 10% did not adhere well to the skin, while concentrations $\geq$ 40% deformed when touched and would not return to its original shape. The optimal levels of adhesion and softness for the Ecoflex Gel adhesion had Slacker concentrations ranging from 20% to 30%. In this paper, we denote the Ecoflex Gel adhesive with 20% Slacker as Ecoflex Y, and that with 30% Slacker as Ecoflex Z.

We evaluated each adhesive for its strength, reusability, cause of pain during removal, residue after removal, and ability to support a motor statically and dynamically. We created 1cm $\times$ 1cm test patches for each adhesive. We defined reusability as the number of times the adhesive could be donned and doffed without losing its strength. Author MC noted whether or not she experienced pain while removing the adhesive from her skin. She also noted whether or not the adhesive left any residue on her skin. The strength was defined as the maximum mass, up to 100 g, that could be supported in both the normal and shear directions without peeling from the skin. The results for the adhesives evaluation are shown in Table I.

We also tested the ability of each adhesive to support a small DC motor (Polulu Low Power 100:1 micro metal gear motor) of approximately 10 g through static and dynamic tasks. In order to attach the motor to the skin during testing, a 3D-printed motor housing was designed with four adjustable feet, as described in Section III-B. The following tasks were completed for dynamic testing: (1) arm swinging, arm dropping, and clapping with the motor mounted on the arm, and (2) walking (6m), running (6m), and jumping (10x) with the motor mounted on the shank. For static testing, the motor was mounted on the arm, and the arm was held in a variety of positions so that the motor was supported in many orientations. While all adhesives supported the motor through both the static and dynamic tests, both Ecoflex Y and Ecoflex Z could not support the motor dynamically for long periods of time.

While the tapes proved to be the stronger adhesives, they lacked in reusability. On the other hand, the reusability of Ecoflex Y and Ecoflex Z appear nearly limitless, confirming the findings in [15], but its strength is lacking. In order to satisfy all of our adhesive requirements, we increased the

TABLE I

ADHESIVES EVALUATION RESULTS

Adhesive	Times Reattached	Pain	Residue	Normal weight	Shear weight
Body Tape	1	no	yes	100+g	100+g
ECG Tape	0	yes	yes	100+g	100+g
3M, 1522	2	no	no	100+g	100+g
3M, 9917	3	no	no	80g	100+g
Ecoflex Y	20+	no	no	30g	80g
Ecoflex Z	20+	no	yes	40g	70g

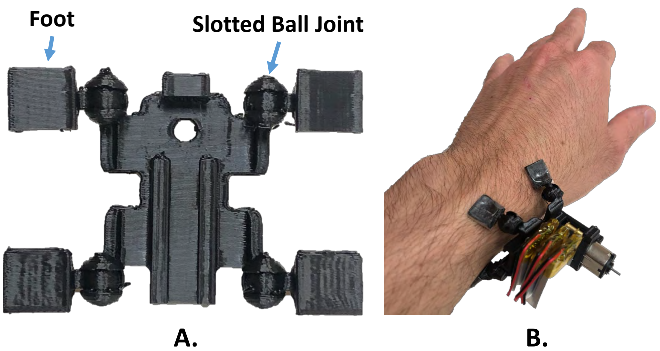

Fig. 2. (A) Slotted ball joints with feet can enable the modules to attach to almost any body location. (B) A module is attached to a user's wrist. The feet are adjusted to match the curvature of the user's wrist.

surface area of Ecoflex Y into a gel pad which proved to increase its strength without leaving residue, as described in Section III-B. This adhesive proved sufficient; it provides dynamic and static motor support, it is reusable, and it can be doffed without leaving residue or causing pain. Although we did not formally evaluate the effects of sweat and oil on the adhesive, we note that the gel adhesives seem to work best on clean and dry skin.

B. Curvature Matching

One of our design goals was to enable the modules to be used on nearly any area of the body. To this end, we came up with two designs to enable the module to be secured firmly to the body, while accommodating differences in the curvature of the supporting body surface. First, we created a design with slotted ball joints to allow the modules' feet to match any curvature, allowing the modules to be placed on multiple parts of the body, as shown in Fig. 2. A single slotted ball joint has two DOFs, allowing the feet to both rotate and move up-and-down. Both the joints and the feet can be added to any CAD design, which can then be 3D-printed as an assembly. We found that this design worked best with double coated medical tape (3M, 1522), described in Table I. The Ecoflex gel pads were generally not adhesive enough to be used with this design.

In the second design, we created a flexible gel pad using Ecoflex Y to attach the modules to the skin's surface. For each haptic module, we developed a custom mold with an opening in the center for the tactor. We first molded a 1mm layer of the Ecoflex Y Adhesive (Ecoflex Gel with 20% Slacker). After this layer cured, a 1mm layer of Ecoflex 00-10 silicone was added on top. Immediately after pouring this layer into the mold, the module housing was positioned appropriately. After this layer cured, the silicone could be removed and was ready to be used on the skin.

Compared to the slotted ball joint design, we found that the adhesive gel pad described in section III-A better distributes the module's weight, and the reaction forces are not easily noticeable. Additionally, the gel pad does not need to be replaced. Due to the reusability and the better distribution of reaction forces, the haptic modules described in this work all use the adhesive gel pad as the adhesion mechanism. However, we believe that the slotted ball joint design with 3M tape might be preferable if the application involves heavy exercise, which could make the skin too sweaty for the adhesive gel pads. We also believe that those who do not have access to Ecoflex Gel but wish to produce the modules might prefer the slotted ball joint design to the gel pad design.

C. Power and Communication

The haptic modules are self-contained, with each module having its own wi-fi board, actuator, batteries and circuitry on-board. All modules use ESP8266-based Wi-fi modules (Ximimark ESP8266 ESP-03) to communicate wirelessly. The wi-fi boards are all connected to a common local area network (LAN), and are controlled through wi-fi using a python script on a computer connected to the same LAN, using the mDNS approach described by [20].

To power the wi-fi boards (rated 3V-3.6V and 170mA) each module contains a 3.7V 290mAh battery (Tiny Circuit) connected to a 3.3V voltage regulator (Adafruit, LM3671). The on-board wi-fi boards, if run continuously, can be used for approximately 2 hours before needing a battery change. In addition, each module contains 1-2 batteries to power their on-board actuators ranging from a single 3.7V 150mAh battery for the vibration motor, to two 3.7V 1000mAh batteries in series for the voice coil actuator.

We also made wired versions during the design process, which were smaller because power and computing were not on board the modules. However, in the end, the benefits of the simplicity of a wireless device outweighed the drawbacks of a larger module size and weight.

IV. HAPTIC MODULES

We used the techniques described in Sec. III to create five re-attachable, wireless haptic modules. The haptic modules are comprised of one vibrotactile module, three skin-stretch modules that provide three different skin-stretch tactile sensations, and one probing module. The needed files to reproduce these modules can be found in [21].

A. Vibration Module

Vibrotactile feedback is currently the most popular haptic modality as it is well understood, low-power, low-cost, and easy to implement [22]. Modern applications include smart phones, navigation, and gaming devices. We developed a vibration module, shown in Fig. 3, which consists of an eccentric rotating mass (ERM) (TOTOT Mini-Vibration Motors 10mm x 2.7mm DC 3V 12000RPM/200Hz) vibration motor.

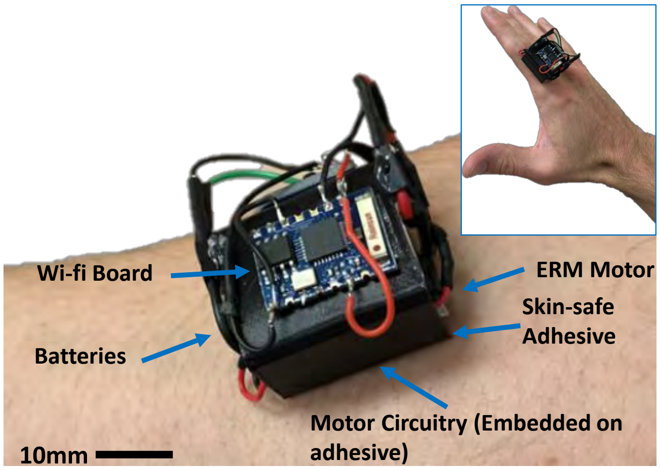

Fig. 3. Vibrotactile haptic module. The top-right figure shows the vibrotactile module on the user's finger for scale. The module dimensions are 25mm × 23mm × 15mm, and weight is 17g.

The motor and its circuitry lies inside the motor housing and are embedded in the Ecoflex Y adhesive with the surface of the motor exposed to the skin. In this design, the Ecoflex Y adhesive helps attenuate the vibrations so that they are experienced most strongly directly under the motor. Similar modules could be made using linear resonance actuators.

B. Skin-stretch Modules

Skin-stretch tactile sensations are generated by a tactor that moves while it is in contact with the skin. We have produced two pure skin-stretch modules, with no relative motion between the tactor and the skin, and one skin-stretch-and-slip module, where the tactor will slide over the skin producing a combined skin-stretch and slipping sensation. However, simple modifications could be made to each module's tactor to create pure skin-stretch or skin-stretch-and-slip cues. All skin-stretch haptic modules use a geared DC motor (Polulu Low Power 100:1 micro metal gear motor) with a magnetic encoder of 12 counts-per-revolution which allows us to implement position control of the motor shaft. The geared DC motors are controlled using a DC motor driver (Adafruit DRV8871) and powered using two 3.7V 290mAh batteries (Tiny Circuit) connected in series.

1) Rocker Module: The rocker module, shown in Fig. 4, creates linear skin-stretch sensations and was inspired by the Rice Haptic Rocker [23]. The rocker's tactor is mounted to the shaft of the motor, so that the axis of rotation is parallel to the supporting surface and the skin is stretched as the tactor rotates. Earlier iterations of the rocker module had a constant radius for the tactor; however, this design does not conform to various curvatures of the skin. Because we anticipate the modules to be mounted on various parts of the body, our rocker module consists of a spring-loaded tactor, shown in Fig. 5A, which ensures the rocker remains in contact with the skin despite the body's curvature. Thus, the amount of skin-stretch l_{stretch} is given by

$$l_{\text{stretch}} = r \sin\theta, \tag{1}$$

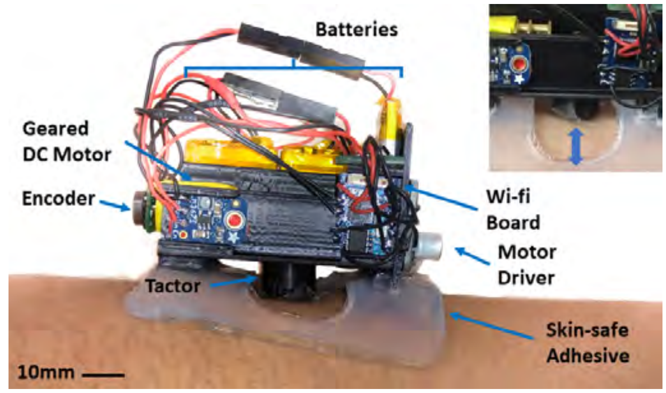

Fig. 4. Rocker haptic module. The tactor's axis of rotation is parallel to the skin's surface and the skin stretches as the tactor rotates about this axis. The module dimensions are 53mm × 27mm × 32mm, and weight is 54g.

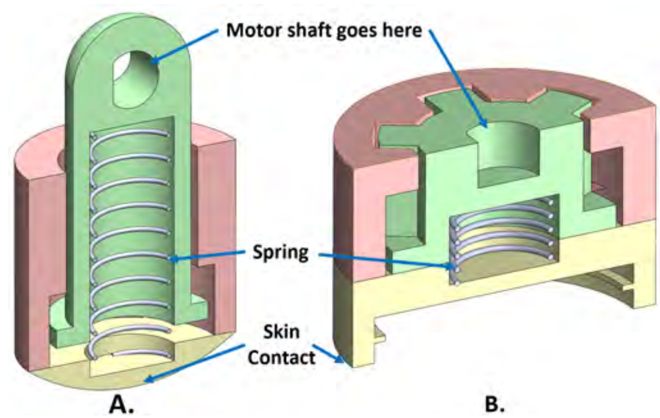

Fig. 5. Cross sections of the spring-loaded tactors for (A) the rocker module and (B) the twister module.

where r is the current radius of the rocker, and θ is the angle of rotation from the vertical. Because the rocker is spring-loaded, the radius r is subject to change depending on the curvature of the skin. To ensure that there is no slippage between the tactor and the skin, we used a piece of adhesive (3M 1522) to secure the tactor to the skin. With the housing walls, the skin can be stretched 7mm to each side from the neutral position, or 14mm in total. However, this range can be increased by removing the bottom portion of the walls to either side of the tactor.

2) Twister Module: The twister module, shown in Fig. 6, provides rotational skin-stretch via a tactor mounted to a motor whose axis of rotation is perpendicular to the support surface. A similar design is presented by Bark et al., whose device used two rubber pads rotating about a single central axis to stretch the skin [24]. Our twister module is a compact design and utilizes a single tactor to apply rotational skin-stretch. As shown in Fig. 5B, the twister's tactor is spring loaded to ensure the tactor stays in contact with the skin. A small piece of 3M 1522 tape helps ensure that no slip occurs between the tactor and the skin. The twister is designed such that the amount of rotational skin-stretch is only limited by the elasticity of the skin. We note that the motor may stall

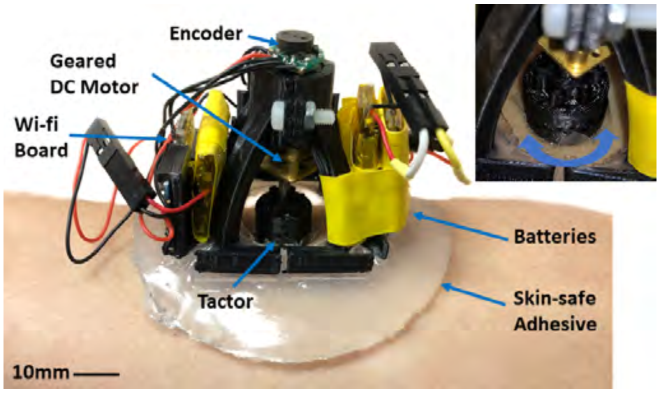

Fig. 6. Twister haptic module. The image in the top right shows a close-up view of the tactor with an arrow indicating that skin-stretch can be generated either clockwise or counterclockwise. The module dimensions are 48mm $\times$ 43mm $\times$ 47mm, and weight is 61g.

at these limits and the user may have to program the limits accordingly.

3) Slider-Crank Module: The slider-crank haptic module, shown in Fig. 7, is inspired by Tsetserukou et. al. who used an inverted 2-DOF five-bar mechanism to provide sliding and stretching tactile cues to the fingertip [25]. We also draw inspiration from Rossi et. al., who created a bracelet with a 1-DOF slider which provided proprioceptive information to the user's forearm [26]. Our slider-crank haptic module uses a 1-DOF slider-crank mechanism to provide sliding tactile sensations that could be used on different parts of the body. The goal of using skin-stretch-and-slip over pure skin-stretch sensations is to reduce the reaction forces at the body-grounded device, which may be a desirable feature to some designers. Nonetheless, the tactor could also be fixed to the skin to provide pure skin-stretch sensations.

The slider-crank module uses a geared DC motor to actuate a slider-crank mechanism which converts the rotational output of the motor to linear motion of the tactor. The sliding mechanism is 3D-printed as an assembly and attached to the motor shaft. The distance traveled by the slider-crank mechanism driven tactor is described by:

$$L_{\text{Traveled}} = \sqrt{l^2 - r^2 \sin^2 \theta} + r \cos \theta, \qquad (2)$$

where r is the length of the crank, l is the length of bar connecting the tactor to the crank, and θ is the angle of the crank with respect to the longitudinal axis of the module, as described in [27]. We designed the slider to be able to move 10mm in both the forward and backwards directions, from a neutral position. We selected a moving range of $\pm$10mm in order to provide the designer with enough space to customize their own sensations. The slider-crank mechanism can be interchanged if longer traveled distances are desired.

C. Probing Module

The probing module, seen in Fig. 8, can be used as a way to mimic touch on the skin in the form of normal indentation. The basis of this module was inspired by the use

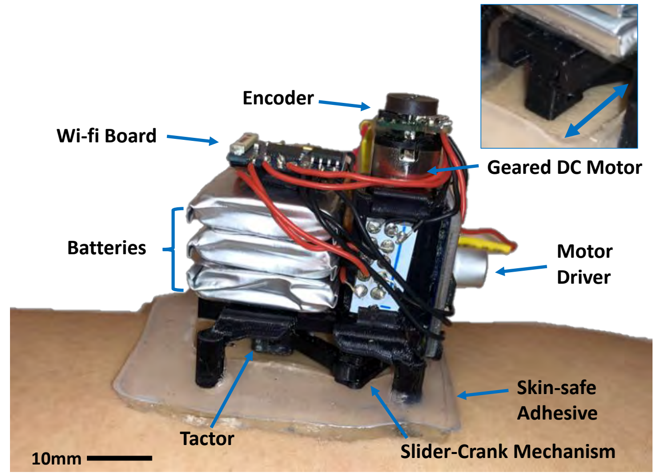

Fig. 7. Slider haptic module. The top-right figure shows a close-up picture of the tactor, and the tactor movement. The module dimensions are 41mm $\times$ 31mm $\times$ 36mm, and weight is 44g.

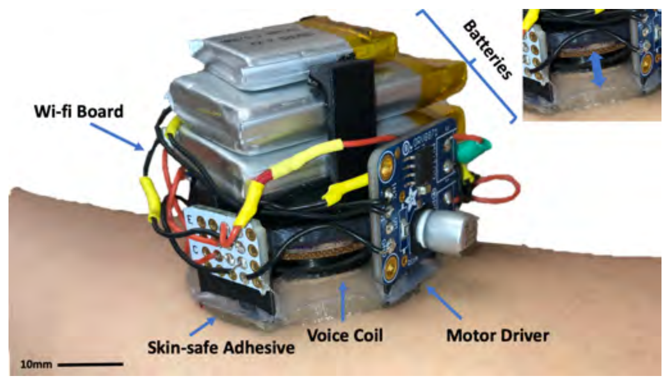

Fig. 8. Probing module with voice coil in a neutral position. The top right image shows a closer view of the voice coil, and the arrow indicates its direction of motion, which is normal to the surface of the skin. The module dimensions are 41mm $\times$ 41mm $\times$ 36mm, and weight is 87g.

of a voice coil actuator (Tectonic Elements TEAX19CO1-8) for probing in Culbertson et al. [28]. The module housing takes on an octagonal shape in order to minimize the area that covers the surface of the skin and to provide a flat mountable surface for the circuit boards.

The voice-coil actuator is controlled via voltage-controlled current-source using a DC motor driver (Adafruit DRV8871) powered using two 3.7V 1000mAh batteries in series.

This module is also capable of producing tapping sensations and vibration sensations with frequencies of at least 350 Hz.

V. Modules System Integration

We believe that the haptic modules presented in this paper have the potential to be powerful tools that enable designers to rapidly iterate through tactile prototypes. As summarized in Table II, each module has several parameters that can be tuned to alter the resulting sensation. When creating tactile displays with haptic modules, designers can vary these parameters until the module produces a sensation suitable for their needs. Designers can also use groups of

TABLE II
HAPTIC CUE PARAMETERS

Module	Cue Type	Customizable Cue Parameters
Vibrotactile	Vibration	Intensity and duration.
Rocker	Skin-Stretch	Amount of stretch, speed, direction, and duration.
Twister	Skin-Stretch	Amount of stretch, speed, direction, and duration.
Slider	Skin-Stretch	Displacement, speed, direction and duration.
Probing	Probing, Tapping, Vibration	Probing intensity, tapping intensity, vibration frequency, and duration.

modules to create complex sensations and displays. They can rapidly iterate over the design of multiple haptic prototypes by changing the spatial arrangement of the modules, the temporal actuation patterns, or by tuning the cue produced by each module.

We note that designers can also make some minor mechanical modifications to the modules to alter the tactile sensations. For instance, designers can change the length of the rocker arm to increase the amount of skin-stretch induced. Similarly, designers can also change the tactor size of the twister to cover more area, use a different surface texture for the slider's tactor, or explore alternative tactor adhesion methods.

VI. FUTURE WORK

In the future, we will conduct a user study to evaluate a person's perception of tactile cues generated by the modules. Unlike previous wearable devices, which are attached to the body via straps or garments, our devices are attached using a local adhesive. The adhesive results in reaction forces, particularly for the skin-stretch and probing devices, when the cues are generated, which may affect the user's ability to sense cues in terms of, say, magnitude and direction.

We believe that our proposed haptic modules will significantly ease the process of rapid prototyping through different haptic displays. To test this hypothesis, we will evaluate the haptic modules through a user study consisting of a group of novice designers to determine whether they can use our haptic modules to create new tactile cues. A graphical user interface will be developed for participants to easily and intuitively program their own haptic devices.

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