A Cutaneous Haptic Cue Characterization Testbed

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Abstract— **Within the field of haptics there is a need for a standardized method of characterizing tactile stimuli and assessing human perception of tactile cues. Most haptic devices are characterized using methods that are often unique to a given experimental investigation, making direct comparisons across studies challenging. In addition, tests involving the comparison of simultaneous haptic cues add a further degree of complexity. To meet these needs, we have developed the AIMS (Adjustable Instrumented Multisensory Stimuli) Testbed, a modular and instrumented testbed that allows for flexible testing of and comparison between haptic cues. In this paper, we present the design of the testbed along with its existing haptic cue modules and sensor systems. Additionally, we examine data and observations taken from a psychophysical study performed using the testbed. Finally, we discuss the potential for this system to serve as a platform capable of reproducibly measuring the effects and interactions for a wide range of haptic devices and cue sets.**

I. Introduction

A current major research thrust in the field of haptics is the development of new wearable devices that can convey a range of tactile cues to the human user [1], [2]. It is difficult, though, to compare the capabilities of different haptic systems and thereby assess their relative benefits. One of the primary difficulties in comparing these systems is the lack of standardization in methods for assessment of haptic systems and cues. Most haptic systems are characterized without context to other systems and to our knowledge there is no standard platform built specifically to enable comparison between tactile cue types.

Previously, testing platforms have been developed for assessing the ways in which people interact with generalized virtual environments using force-feedback systems [3], [4]. Such platforms have not yet been proposed for rigorous evaluation of cutaneous haptic devices. The few examples of testbeds that handle multi-modal cues, in this case visual and tactile, were designed primarily to measure sensory perception [5] and do not characterize differences between different types of haptic stimuli. Further, the link between haptic perception and the mechanical cues that cause them is a developing area of research. For rigorous and direct comparison of haptic devices, there is a significant need for a consistent and reproducible testing standard which can be used to compare different modes of haptic mechanical stimulation applied directly to the skin, with consistent testing and data collection conditions.

Vibration has been the most extensively implemented type of tactile cue, and has been successfully used to convey a wide range of haptic information. While vibration cues are suitable for many haptic tasks, they are affected by the desensitization of the skin to vibration, and from interference between vibration cues [6], [7]. In response to these limitations, recent haptic devices have been developed to use combinations of different types of haptic stimuli to transfer more complex information through the haptic channel in a smaller and more wearable package [8], [9]. Previous investigations into multi-sensory haptic devices have even succeeded in conveying language solely through the haptic channel [8], [10]. Despite these exciting developments in multi-sensory haptics and the breadth of applications that seem well-suited to such haptic stimuli, new challenges have arisen that were not present in traditional kinesthetic or single-modality haptic displays.

Foremost among these is the issue of interference be-

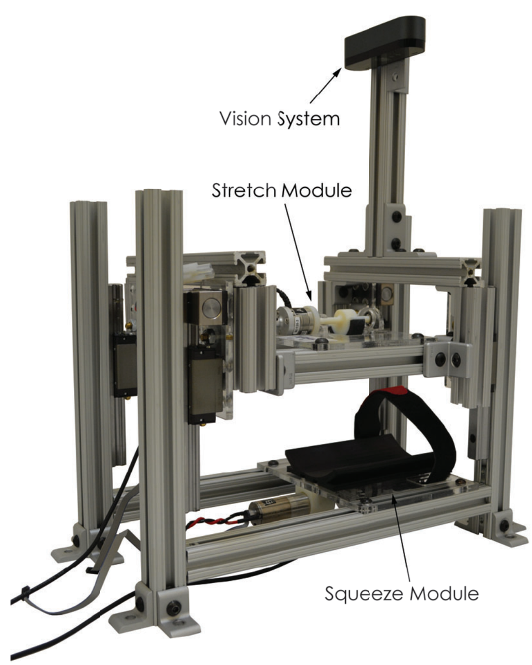

Fig. 1. A modular haptic testbed has been developed to allow for evaluation of single and multi-sensory tactile cues. The testbed integrates various sensing modalities to characterize the device interactions with the human user, and to facilitate psychophysical evaluations.

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tween different haptic cues being provided to a user. This interference has been observed in previous multi-sensory haptic studies [10]. Additionally, interference between vibration cues has already been identified as a factor affecting perception [7]. In order to accurately assess this developing class of haptic devices, a generalized haptic testing platform must be capable of delivering different modes of haptic stimulation simultaneously in a consistent manner, while also simultaneously collecting data sufficient to analyze the comparative effects of the different stimuli.

To meet these needs, we have developed a haptic testbed system - the AIMS (Adjustable Instrumented Multisensory Stimuli) Testbed. This system is a modular haptic testbed designed to be used for psychophysical testing and haptic cue characterization for a number of different haptic modalities, displayed individually or simultaneously. The system's modular design is intended to allow flexibility in testing configurations while maintaining a consistent presentation of haptic cues and data recording methodologies. Our system provides multiple methods and platforms with which modes of haptic stimulation can be realized, as well as a number of standardized sensing tools which can be used for direct comparison of interaction properties and perception. This experimental system represents a significant step towards a more rigorously defined and standardized approach to the assessment of cutaneous haptic cues.

II. Design & Fabrication

The haptic testbed, depicted in Fig. 1, was designed to be simple to construct from readily available stock materials and to allow for easy and comfortable human subject testing. The primary frame of the device is constructed of aluminum t-slotted beams arranged to form a scaffold onto which multiple testing modules can be affixed. The frame has overall dimensions of 14 in. by 7 in. by 12 in. Each beam is secured onto an aluminum optical breadboard clamped onto a work bench. Both upper and lower tiers are made of t-slotted beams that span the horizontal length of the testbed. The upper tier is mounted onto four linear guide rails that allow for height adjustment; two hand brakes attached to these rails are used to secure the position of the upper tier. A beam protrudes upwards from the upper tier which supports a mounted camera, such that the experimental region can be captured. The lower tier is secured rigidly to the main frame by corner brackets.

The testbed was designed to be highly modular. Haptic devices are replicated as testbed 'modules', each fully actuated and independent. Each component in these modules can be replaced or reassembled quickly and easily. Further, by separating each haptic cue into a separate module, we can rapidly test different haptic cues. Each haptic cue module on the testbed can be customized to change testing parameters including device component materials or module positioning. This was a major design consideration, as the testbed is intended to be used for a variety of cue characterization experiments and haptic perceptual studies involving human subjects. None of the fixtures in the testbed are permanent, and all components are fitted together using removable fasteners.

For initial design and validation purposes, two cutaneous haptic cue modules have been fabricated - one for assessing skin stretch and the other for radial squeeze. A third module for assessing rotational skin stretch cues was also constructed, and additional modules are under development. Each module consists of an acrylic platform, a Maxon Motor (DCX22S 12V) DC motor with GPX22HP 83:1 planetary gearhead, an ATI Nano25 6-axis force-torque transducer, and an end-effector. The acrylic platform is secured onto the t-slotted frame using slot inserts and its position can be adjusted laterally when the fasteners are loosened.

The stretch module (Fig. 2) utilizes a simple rocker design to deliver cues. The end-effector is a 3D printed, rubber coated, semi-circular tactor based on the Rice Haptic Rocker [11]. When pressed against the subject's forearm and actuated by the DC motor, it produces a mild skin shear sensation that is perceived as a stretch cue. The stretch rocker is mounted between a bearing at the edge of the platform and the tool side of the Nano25 transducer. A 3D printed adapter is affixed to the mounting side of the Nano25 transducer to the DC motor's shaft. The DC motor is securely held in place by a 3D printed mount that is fastened directly onto the acrylic platform.

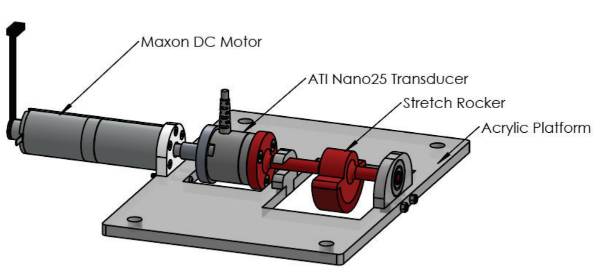


Fig. 2. Isometric view of stretch cue module. The stretch mechanism is driven by a DC motor with a force-torque sensor placed in series, allowing for accurate measurement of the loads exerted on the subject's forearm.

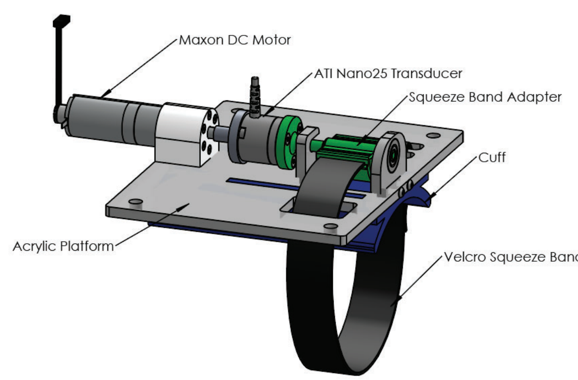


Fig. 3. Isometric view of bottom of squeeze cue module. The module is compatible with both the lower and upper tiers of the testbed.

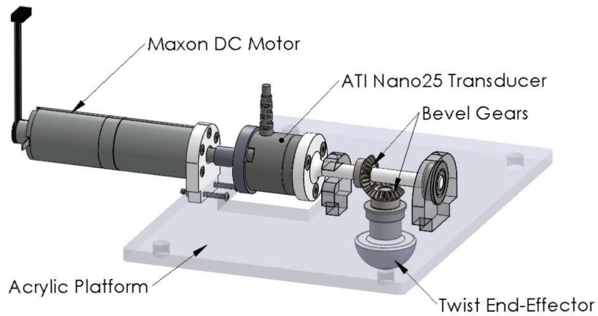


Fig. 4. Isometric view of twist module. While the direction of action differs from that of the stretch and squeeze modules, the loads involved can be measured by the same sensor configurations.

The squeeze module (Fig. 3) is structurally similar to the stretch module, with the exception that a squeeze band adapter was used instead of a stretch rocker. The design is based on the squeeze component of MISSIVE [10] and utilizes a velcro squeeze band. This squeeze band loops through the squeeze band adapter and around a subject's forearm such that when the adapter is actuated, the band tightens around the subject's forearm and creates a squeezing sensation. During experiments, the subject's forearm rests on a 3D printed cuff mounted on the opposite side of the acrylic platform, which ensures the alignment of the subject's forearm with the stretch and squeeze modules.

The twist module (Fig. 4) features a hemispherical end-effector that is actuated by a DC motor through a 90 degree bevel gear system, which translates the rotational motion of the DC motor perpendicular to the end effector, creating a twisting sensation [12].

The haptic testbed allows researchers to easily experiment and test with different combinations of modules, or even implement novel cue types, allowing for a wide variety of cutaneous interactions to be explored, evaluated, and quantified.

III. Actuation & Instrumentation

While there are many types of actuation methods for haptic devices, a majority of devices rely on compact DC motor actuation to deliver cues to the body. The DC motors in the stretch and squeeze modules of the testbed use a position controller featuring position data reporting, while also collecting force and torque data from on-device sensors, and video data from an attached camera. These devices are integrated such that data are gathered in an organized and time-synchronized manner, allowing for collection on a single control computer. Not only is this approach convenient in terms of data management, it also ensures that data are recorded and stored correctly, as any problems with a piece of equipment can be observed and managed by the control computer. This centralized control and instrumentation approach allows for flexibility in regards to the actuators and sensors used, as additional devices can be easily integrated into the existing control and data recording framework without having to deal with complex device-synchronization schemes.

The stretch and squeeze mechanisms described in Section II are actuated with a set of 12V DC motors. The DC motors are controlled by Maxon Motor EPOS4 Positioning Controller Modules, which are in turn controlled by a C++ based executable written for use with the testbed system, using the Maxon EPOS command library. These motors were selected due to their high torque and speed output at the desired power level and capability in handling the wide range of motions needed for a generalized testbed. They also satisfy the expected torques for the squeeze module as determined by experimental force and torque measurements on similar systems. Closed-loop position control is implemented in each EPOS4 controller in the stretch and squeeze mechanisms at a rate of 2.5kHz. Additionally, the PID control system allows for accurate measurement of the position of the motors (and, by extension, the movement of the stretch tactor and squeeze band) which can then be related to other collected sensor data. Sample data for motor position and the force-torque sensors detailed below can be seen in Fig. 5. This position data reporting allows for further analysis of user-device interaction effects, and better informs analysis of collected psychophysical data. In other experimental cases it may be necessary to use other control methods - the motors are compatible with a large number of control schemes, and the control programs are designed such that it is possible to substitute in different methods of control. In particular, the force-torque data are time-synchronized and available to the control program such that it is possible to implement a force-feedback control system.

In order to compare the effects of different haptic stimulation cues, it is necessary to measure the forces of interaction between the human subject and device under study. To accomplish this, the testbed was outfitted with force/torque sensors. In each of the stretch and squeeze modules, force/torque sensors are integrated in series with the DC motors, such that the loads being transmitted from the motors to the devices can be measured directly. We selected ATI Nano 25 6-axis transducers with torque sensing ranges of 3 Nm and resolution of 1/2640 Nm in the z-direction (along the motor axis), and 1/1320 Nm in the x- and y- directions. The force sensing range/resolution is 500 N / 1/16 N in the z-direction, and 125 N / 1/48 N in the x- and y- directions. These sensors are integrated into the control and data recording executable program which manages the experimental trials via a National Instruments PCIe6323 XSeries PCI Express DAQ. This system is capable of recording 6-axis force and torque data from both sensors simultaneously at a rate of 1000 Hz.

The video recording component of the testbed consists of a Logitech BRIO webcam mounted 25 cm above the upper module. The camera is mounted via a standard screw for easy removal and adjustment, and the mounting platform can be moved within a large range above the device frame

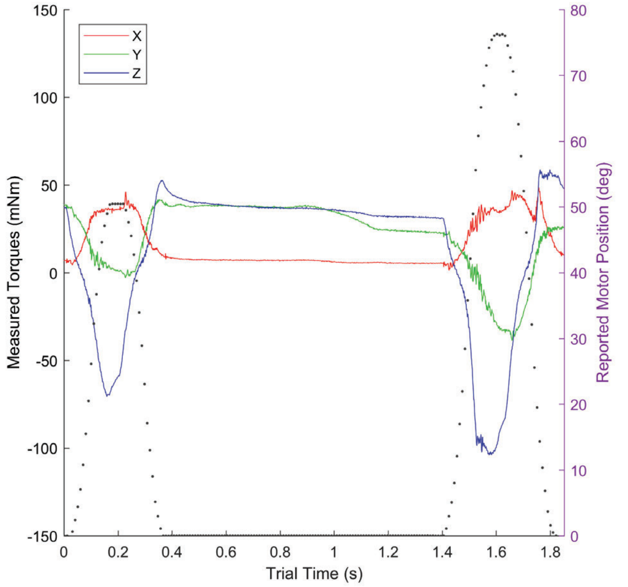


Fig. 5. Stretch module motor position in degrees overlayed onto x-, y- and z- axis torque outputs when stretch module is driven to 52°, back to 0°, waiting for 1 second then driving to 78° before finally returning to 0°. The force and torque data were reported from the sensors at 1000 Hz and the position data were reported from the motor controller at 100 Hz. Note that the PID controller operates at 2500 Hz; the 100 Hz reporting is due to hardware bandwidth limitations.

via adjustment of its mounting brackets. The camera is connected to the device-control computer via a USB 3.0 cable, and is controlled through the OpenCV 4.0 library. The combined system is capable of capturing video at 1080p resolution at 30Hz, synchronized with the force and position data provided by the other devices. See Fig. 6 for sample data. This is controlled in such a way that video data are collected on an as-needed basis - in the case of the validation experiment detailed in Section IV, this consisted of 1,400 one to two second videos taken over the span of approximately 45 minutes in a single testing session.

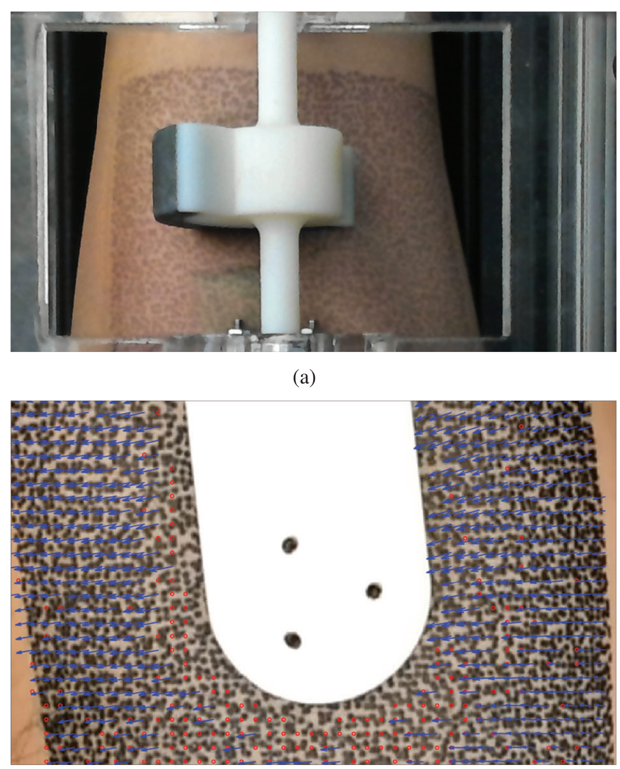
In addition, the libraries and control software, as well as hardware mounts, are designed such that it is possible to configure the system to utilize other cameras and capture settings depending on the needs of the particular experiment. Capture is performed using a generic camera protocol. As a result, swapping of systems is possible with only minor modification of the control system. Some systems, such as FLIR or high-speed cameras, would require additional modification - and possibly additional capture hardware - but should be compatible with the data handling and synchronization methods used by the control program.

In regards to sensors outside of the types already implemented, the testbed design is structurally open such that there is sufficient room for the placement of most sensors regardless of their physical profile, with room for adjustment to the various components to allow for the placement of most haptic devices and systems. The control and monitoring of the existing testbed systems is managed by a custom-made (and open-source) C++ library which can be packaged into a Windows executable. Through modification and rebuilding of this code it is possible to integrate most control and sensory systems for which there are existing C++ libraries. For other systems various hardware- and software-level workarounds are possible.

IV. Device Validation

To demonstration the functionality of the testbed and its various modules and sensors, a perceptual cue comparison test was performed which aimed to examine the effects of interference between squeeze and stretch cues delivered to the arm. This test necessitated the simultaneous delivery of both stretch and squeeze cues within close spatial proximity on the subject's forearm, and provided an excellent opportunity to demonstrate the capabilities of the proposed haptic testbed.

Thirteen subjects (six female, eleven right-handed, 20-29 years old, average age 23) participated in the experiment in which four combinations of haptic cues were displayed to the forearm: squeeze varying alone, stretch varying alone, squeeze varying with constant stretch interference, and stretch varying with constant squeeze interference. For



(a)

(b)

Fig. 6. (a) Still frame from experimental video data focused on the region of interaction of the stretch device. The ink pattern seen is a speckle pattern stamped onto the skin using skin-safe temporary tattoo ink and a custom-made stamp. This pattern can be used with digital image correlation algorithms to determine the effects of stretch intensity on skin deformation and rocker slippage - a secondary goal of the experiment performed. (b) Example tracking of speckle pattern on skin using Digital Image Correlation Engine (DICe).

each condition, the cues comprised seven distinct magnitude comparison points, ranging between 13 and 91° of motor rotation for both stretch-varying and squeeze-varying cases. Each trial consisted of a reference cue at 52° of rotation and a comparison cue, each with or without interference from a 52° reference cue on the non-varying device, delivered one second apart. For each point of comparison, 50 trials were performed. At the end of each trial, the subject would indicate whether the first or second cue provided a stronger haptic sensation via key press. Details of the experiment are described in [13]. A total of 4200 cue presentations were delivered to the forearm of each subject over the course of two one-hour testing sessions, with individual conditions conducted in 15-25 minute blocks. An example of subject positioning during this experiment can be seen in Fig. 7. All participants gave informed consent and all procedures and methods of the experimental protocol were approved by the Rice University Institutional Review Board.

During each trial, motor position, force, and torque data were collected for each haptic module, and video data were collected with a focus on the stretch module's effect on the subject's skin. These data were collected alongside the experimental subjects' responses to the experimental conditions. All data were automatically compiled and organized by subject and trial conditions for analysis. For each subject, roughly 20 GB of data were collected, with the majority of that being video data.

A rapid, high-repetition experiment such as this provides an excellent testing scenario for a generalized testbed, as it necessitates a high degree of device consistency and robustness. Additionally, the large number of trials across subjects performed for each condition allows for human factors affecting device performance, ergonomics, and other user-oriented concerns to be studied and addressed. To this end, upon completion of the experiment, subject feedback on the experiment performed and device used was obtained via a Likert scale survey, in which subjects rated various factors of their experience and provided feedback on the device.

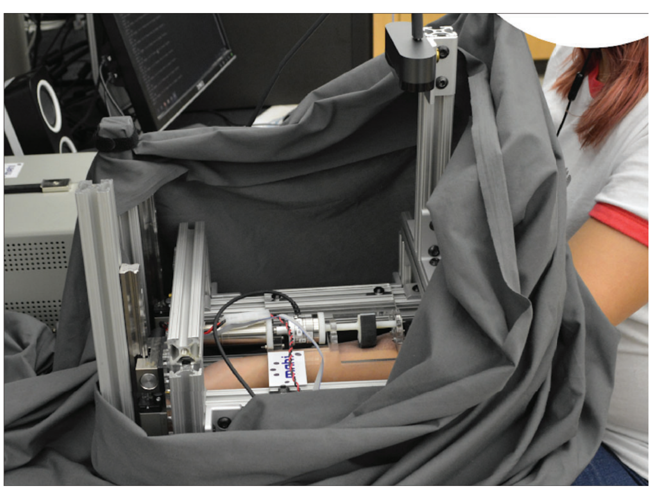


Fig. 7. Device in use during validation experiment. Note that subject's view of the device was obstructed and the subject listened to pink noise to prevent them from hearing the actuation of the motors.

V. Results

To evaluate the utility of this testbed for collecting psychophysical and interaction force/torque data during extensive testing, we conducted a prototypical cue perception experiment. The testbed delivered more than 18,200 trials, involving 54,600 individual module actuations, for which 270 GB of data were collected. While some testing failures did occur, these were relatively minor and did not result in harm to subjects or the device, and did not significantly interrupt testing. The only significant interruption was caused by failure of a 3D printed Rigur RGD450 plastic coupler in the squeeze module, which failed under repeated torsional loads. The component was replaced with a carbon fiber PLA printed version of the component, which did not fail throughout the remainder (roughly 90%) of testing. In future module designs, this component will likely be machined from aluminum or printed from a stronger material.

Our experience with this example experiment indicates that the system is, with minor adjustments, robust and reliable to a degree sufficient to facilitate most comparative haptic studies. While efforts should be made to ensure that replacement components and data redundancies are in place in case of unexpected failure, there are no major points of concern in the operation of the device.

Based on survey feedback, subjects found the system to be neither particularly comfortable nor uncomfortable, though subjects reported that the device as used was intuitive to interact with and interpret. Anecdotal observation and survey written responses did not indicate any major problems, though they did point to some minor areas for possible improvement. Six of the thirteen subjects found the cues delivered to be mildly irritating to the skin, of which three described the discomfort as being primarily after or towards the end of testing. While this is not an issue that can be completely alleviated in this type of testing, since it involves many repeated trials over a range of intensities, steps can be taken to reduce irritation. Strategies to address these concerns could include breaking up the experiment into subsections to allow for more breaks, and adjusting cue magnitude range to prevent unnecessary discomfort.

There were no significant issues related to device ergonomics, though they were a factor of consideration and assessment. The rigid arrangement of the device components within the frame and their static placement on a workbench surface meant that subjects had to position themselves such that they were able to hold their forearm within the device while operating the computer keyboard. This did not prove to be a major problem for most participants, although some found the positioning mildly uncomfortable. Additionally, the placement of the upper stretch module relative to the lower module platform, and the angle at which the subjects placed their forearm within the device, meant that in most cases stretch cues were delivered slightly off from the center line of the arm. While this was a minor issue and did not significantly affect testing (as all comparisons were within-subject and arm positioning was not recorded as a data point for comparison), it was a minor inconvenience. In future iterations of the device and its modules, it may be prudent to construct one or both of the modules at a skewed angle in order to allow for a more comfortable positioning of the forearm.

VI. Discussion

The modular haptic testbed features two key capabilities. First, it can be outfitted with a number of different actuation modules, enabling the evaluation of several types of cutaneous haptic cues, either individually or in concert. Second, the testbed incorporates a variety of sensing capabilities including position, force, and video capture to assist in the characterization of the cue to skin interactions.

To demonstrate the capabilities of the testbed, we conducted a psychophysical experiment (for details, see [13]). The haptic testbed system was used to successfully perform an interference-assessment experiment with a high degree of reliability and consistency. Because the system is designed to be generalizable and reusable, it can be extended for use in other experimental protocols and device evaluation scenarios.

Numerous further experiments are planned for the existing modules and sensor equipment currently in place on the testbed. Chief among these are investigations into the relationships between the sensation of stretch and squeeze from the haptic modules described above and the displacement of the skin. This can be measured by comparing the mounted camera, force/torque, and motor position data to user feedback, which benefit from the the time-synchronization of data collection. Additionally, there is interest in investigating the force-dependence of the perceptual effects observed in the psychophysical study discussed in Section IV and in [13]. This may involve re-performing the experiment with force-normalized cues or altering the test setup to measure the force at a different point within the stretch and squeeze mechanisms - both of which are easily accomplished with the current testbed.

Although the stretch and squeeze modules used in validating the testbed design were based on existing haptic device designs, a wide variety of devices can be functionally reproduced using this testbed. This would allow for validation and investigation into haptic mechanism characteristics to shine light on effects such as interference and force dependency on cue recognition, thereby allowing for both a better understanding of the devices under study and the fundamental interactions taking place. Additionally, the static and easily modifiable nature of the testbed allows for such testing to be performed in a more reliable and straightforward manner than can be accomplished with on-body test devices, as it removes many of the subject-dependent factors relating to such devices.

VII. Conclusion

We have presented a modular cutaneous haptic cue testbed that enables evaluation of such cues in psychophysical experiments, and quantification of the interaction effects between device and skin via position, force, and video capture. The AIMS Testbed performed well in experimental testing, and was able to reliably deliver haptic cues and measure user responses as well as force, torque, motor position, and other factors relating to user interaction. In addition to its current capabilities, the system can be easily expanded with new modules and sensors to perform other haptic experiments, and is particularly well-suited for comparisons of the effects of different cues and stimuli. The AIMS Testbed can be duplicated by independent groups with relative ease, such that experiments can be replicated or modified independently. Through this, different haptic devices and methodologies can be assessed in a controlled and standardized manner, allowing for meaningful comparison and investigation.

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