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Board 134: The HapConnect: Teaching about Haptics and Inclusive Design with Modular, Wearable Technology

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The HapConnect: Teaching about Haptics and Inclusive Design with Modular, Wearable Technology

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Abstract:

In this paper, a learning module is introduced to teach undergraduate engineering students about the principles of haptics and inclusive design thinking through wearable technology. To that end, a novel wearable haptic (touch) device was created, referred to as the HapConnect, that contains modular vibration components for student teams to explore the use of haptics in a simple context, design and create their own versions of the device, and deploy it in a use-inspired setting. Through a series of lecture and hands-on design sessions, student teams were tasked with employing the HapConnect to navigate through a maze exclusively by the sense of touch. This paper evaluates student confidence in topics – such as haptics, human perception, wearable devices, and inclusive design – discussed throughout the module, feedback and performance of the HapConnect, and team design choices to complete their activity. Results indicate that student learning and confidence increased throughout the activity, while each team's success in the maze was attributed to their differing design choices.

Keywords **-** haptics, wearable device, modular, learning tool, inclusive design

1. Introduction

As technology design and educational experiences rapidly evolve, they often neglect one key element – touch. Touch is one of the earliest associated learning modalities for humans, and data show its neural, behavioral, and physiological contributions to early childhood, reinforcement-based learning [1]. Current trends forecast the increase of haptic (touch) integration [2] [3] into consumer technologies [4] [5], healthcare [6], and telerobotics [7], yet many technologies designed to date are heavily focused on visual and auditory capabilities. Similarly, many educational experiences have transitioned to digital/online platforms, and are also heavily shaped through vision and auditory senses [8]. Haptics – the science and technology of touch – has the potential to address this gap, by creating an experience of touch through the application of forces, vibrations, or motions to a user via an interface or device [9]. This paper explores the possibility of incorporating a wearable haptic device into a short learning module deployed in an engineering course to do the following: 1) introduce burgeoning engineers to the concepts of haptics and inclusive design approaches, and 2) to bring tangibility into the classroom itself.

1.1 Related Works

Touch interactions, whether mediated via devices or intrinsic to a kinesthetic user experience, act as facilitators for teaching and learning. Various approaches exist to improve student learning at different ages by utilizing the sense of touch, such as advancing letter recognition skills in children [10], or combining tactile stimuli with sketching to create stronger recall of objects in college-age students [11]. Comprehensive literature reviews dive into the psychological principles of haptics in learning [12], potential for haptics to prominently enter education [13], and pedagogical methods to incorporate touch technology into education [14]. These findings all demonstrate the advantages of using touch, such as improved language retention and higher engagement with material within learning environments, and advocate for the continued utilization of technology as a facilitator for education.

A number of haptic devices have been deployed to augment the educational learning process. The Haptic Paddle is a popular device developed at Stanford University [15] to present simulated dynamic systems via force feedback, with applications being presented in a variety of classroom settings [16] [17] [18] [19]. Other approaches have taken advantage of commercially available LEGO robotic systems [20], the Phantom Omni device [21], and Novint Falcon device [22] in order to adapt them as learning tools for coding, physics, and geometry. In addition to grounded form factors, wearable haptic devices have been developed that are able to deliver force feedback and map sensations to language building blocks [23].

While force feedback devices provide rich user experiences, they come with trade-offs in terms of design complexity, form factor, and cost. The use of vibratory feedback is another mechanism to provide haptic (tactile) feedback that can often be smaller and simpler in design. Snaptics is open-source hardware that combines force and vibration feedback to create a low-cost haptics platform for rapid prototyping, while lowering technical barriers to entry for designers interested in modification for learning applications [24]. Wearable vibration devices have additionally been shown to facilitate language learning through mapping patterns to phonemes [25]. Other applications have seen vibration used to correct movement for learning bodily motions [26], as well as enhance motor learning and navigation [27].

Of equal importance to functionality is the device's value as tools for promoting inclusivity, especially for individuals with disabilities [28]. By adapting systems like the Phantom Omni, the force feedback device can be used to teach 3D shapes to children who have blindness [29]. Commercial touchscreens and computer-based haptics graphs are also capable of translating 2D graphics into rich multi-modal experiences via various haptic interfaces [30] [31] [32]. Smart haptic tangibles, that can be reconfigured and connected to educational simulations, are also being developed to teach geometric concepts for individuals with blindness and low vision [33].

While several devices have been introduced into a variety of classroom settings to enhance the student learning experience, fewer devices have been focused specifically on teaching the concepts of haptics and touch-centered design, with a lens toward inclusivity, to aspiring engineers. To address this need, the HapConnect is presented – a modular, reconfigurable, vibration-based wearable haptic device – with the design purpose for teaching undergraduate engineering students about haptics and inclusive design (see Figure 1).

1.2 Contributions

This work presents a short classroom module (four, 1 hour 15 minute periods) examining student learning about haptic feedback, both as a concept and as a means of determining how system design may benefit from haptic capacities. The classroom module consisted of two separate parts: a lecture component and an activity component, with pre- and post-questionnaires administered to investigate how student understanding of haptics and inclusive design changed after participating in the lecture and activity. The objective of the learning module was to investigate two main research questions:

1. How using a customizable, haptic wearable device increased student understanding of haptics and inclusive design practices
2. How separate student teams design their devices differently for their final day deliverable.

To explore this space, the HapConnect was created under the intention of providing students with a means to experience haptic technology, specifically vibratory feedback, through a simple, reconfigurable platform. Through an activity utilizing the HapConnect, students were introduced to system design that values inclusivity via touch, which provided a unique application to demonstrate the human haptic capacity. The novelty of the device is highlighted in its low-cost nature (manufactured under 60 USD) and its relative ease for customization of motors with minimal to no prior knowledge of the system (see Section 2). This plug-and-play design provided students with a chance to utilize wide ranges of vibration capabilities simply by changing the orientation and locations of the vibration motors. Students were encouraged to experiment with the capabilities of the HapConnect, create their own solutions, and then apply their learning through an real-world scenario to experience the affordances of haptic technology.

2. Device Description

The HapConnect consisted of two components: a wearable vibratory system (see Figure 1) and a corresponding controller system (see Figure 2). The HapConnect architecture was designed such that one student wore the vibration system around their wrist, which provided vibrotactile feedback, while another student controlled the actuation of the vibration from the controller system. A one-way communication system was implemented for the handheld controller specifically to enable students to provide real-time, wireless control of the vibration feedback for the in-class experimentation (detailed in Figure 2).

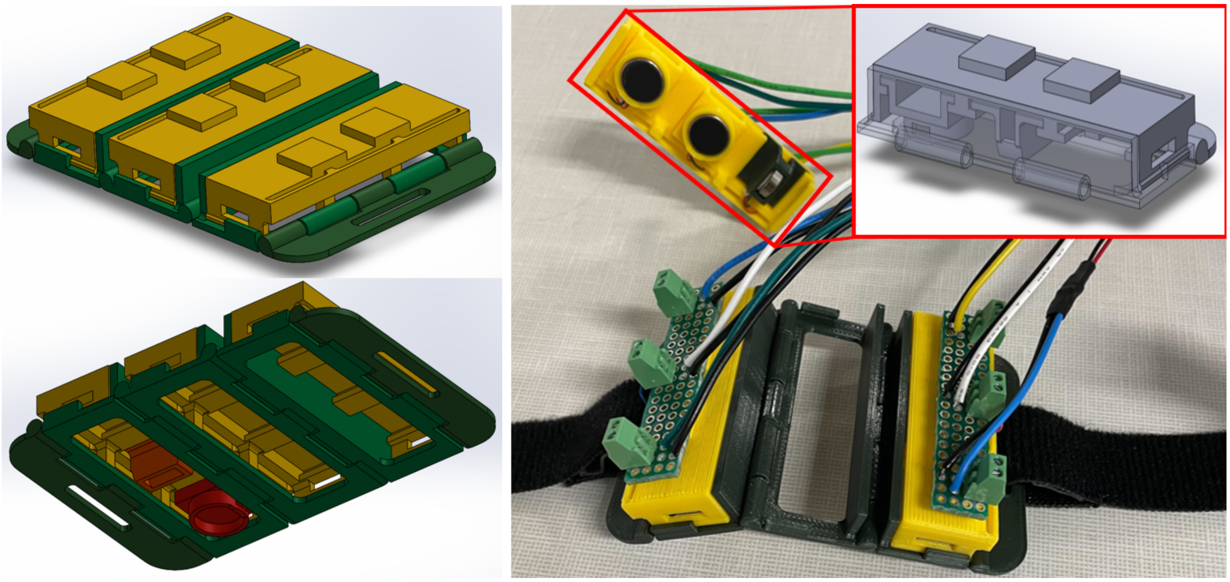

Figure 1: HapConnect vibration system with CAD solid model (left) and physical model (right) with exploded view of the rail snap-fit component for quick connection of vibration motors

The goal of the HapConnect was to provide an easy-to-design, reconfigurable system that enabled students to explore vibrotactile feedback in the design process, and to use it in the context of a navigation-based class project focused on principles of haptics and promoting inclusive design thinking. With that in mind, a number of design requirements had to be met for the device. First, the design needed an easily changed component system for rapid adjustments, providing each student team with the ability to modify the HapConnect in their own fashion. With the condensed timeframe for the learning module, simple motor changes were desired instead of in-depth code adjustments to reflect physical changes to the device. The device additionally needed to take up minimal arm space, conform tightly to the skin, and adjust for variability in arm size in order to allow for direct skin contact of the vibration motors. Finally, remote communication between the systems was necessary to support project implementation. To achieve realistic levels of control with minimal delay in signal, a Bluetooth system was integrated to allow for remote communication between the vibration and control systems.

2.1 Vibration and Control Systems

The vibration system (see Figure 1) was worn on the left forearm and secured by a strap, while the control box containing the Bluetooth module was held in the left hand. Vibration was chosen as the primary feedback modality for the HapConnect, mostly due to the component size of the vibration motors, as well as the ability to create a dense network of distinctive signals on a person's skin [34]. Additionally, vibration is one of the simplest forms of haptic feedback, providing a nice platform for introducing haptic design in the classroom.

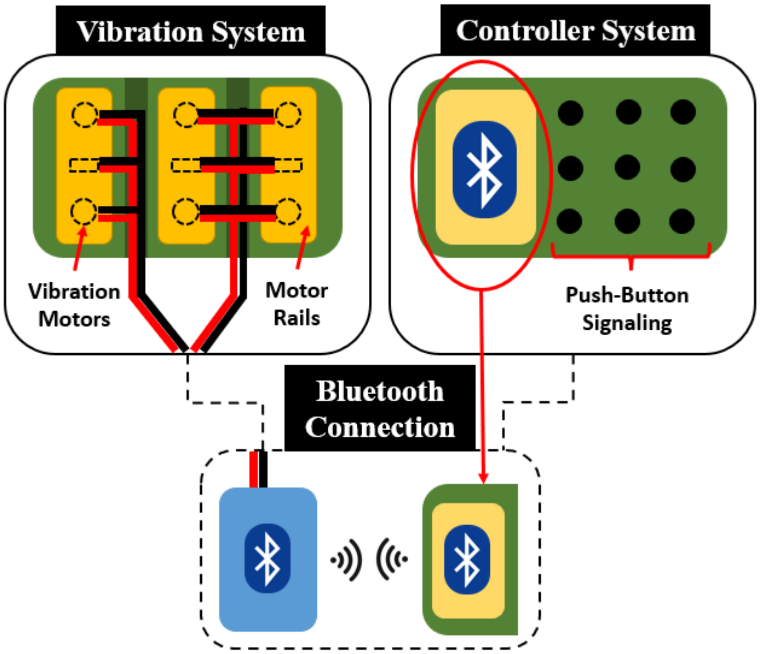

Figure 2: High-level schematic of the HapConnect device with its individual components and their means of connection and communication

Overall, the HapConnect can fit up to nine vibration motors (Vybronics VC0720B coin motors), in a 3x3 array that can be oriented either vertically (e.g. turned on its side) or horizontally (e.g. flat to the skin). When using the two orientations and empty spaces on the grid, students could create just under 20,000 different combinations for the HapConnect. The vibration system consists of three rails that attach to the base mount through snap-fit connections to create an interlocking mechanism between the two separate pieces. Between rails, a multi-hinge mechanic allowed the separate columns to join together as a full base which connected the system together.

The control system was designed to be very simple in nature, enabling a 1:1 mapping between push button control and vibration motor activation and minimizing the learning curve associated with device functionality. This was handled through nine push buttons laid out in a similar 3x3 grid orientation, with each push button mapping to a specific motor on the vibration system. The control system was handheld by students with the push button on/off signal activations being used to communicate with the vibration system via an Arduino Nano and Bluetooth connection.

3. Classroom Module

The engineering class consisted of 25 participants, with the gender distribution of the class being identified by the professor as standard for the course and level. A majority of the students were of college sophomore-level, and ranged from freshmen to seniors. Prior to the module, students had little to no experience with concepts covered by the study, but possessed at least one year of engineering fundamentals. This study was approved by the presiding university's Institutional Review Board.

3.1 Lecture Overview

As introduced in the first section, the module was spread over four classes, each being 1 hour 15 minutes. The first class day was split into two parts: a 45 minute lecture over haptics and inclusive design, followed by a 30 minute ideation session where students would apply the newly learned concepts to sketch their own solutions to a haptics-based project. Table 1 outlines the breakdown of the lecture and its respective concepts.

Teaching Concept	Concept Breakdown
Haptics	1. Definition and Terminology 2. Broad Categorization 3. Feedback Methods
Human Perception	1. Four-Channel Theory 2. Detection Thresholds and Weber Fractions 3. Human Vibration Perception
Wearable Devices	1. Affective Designs 2. Effective Designs 3. Types of Vibration Motors
Inclusive Design	1. Definition and Mindset 2. Adaptive Accessories 3. Design Customization
Application	1. DeafBlind Community and Intuitions 2. Activity Description 3. Ideation Session

Table 1: Compiled list of material delivered during the lecture portion of the learning module

At the end of the lecture, the final project was announced and students formed seven teams to begin a team ideation session on how they would accomplish the challenge. Teams were given the open-ended task of designing a technology that would allow for maze navigation through haptic sensations, where the navigator would be blindfolded and wearing noise canceling headphones. This meant the directions would be through the haptic sense, and guiding had to be performed exclusively through the device. This process was to understand, with no prior interaction to the HapConnect, if similar design themes would emerge amongst the students, and if these would factor into their final project. Some examples generated by the teams included shoe implants, compasses, wrist straps, ankle cuffs, gloves, and bodysuits (see Figure 3).

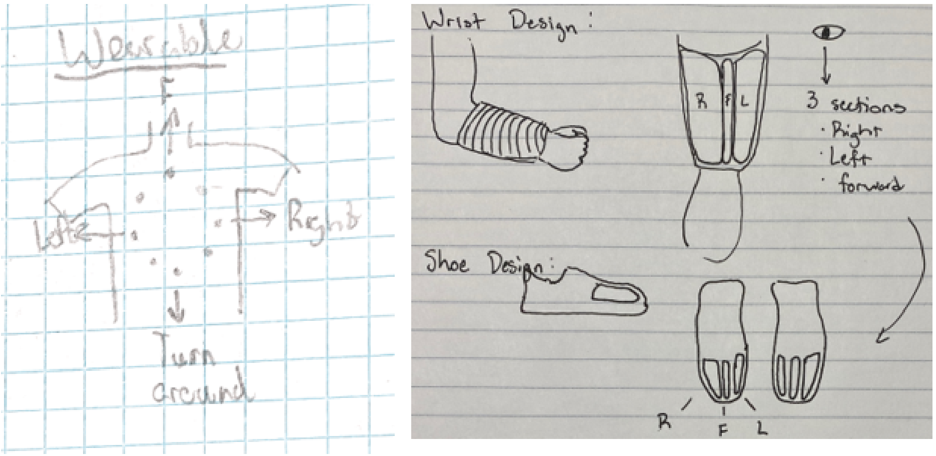

Figure 3: Student sketches from their ideation session of haptic device design following the lecture portion of the learning module

3.2 Activity Overview

Once the ideation session was complete, the next two class periods were dedicated to introducing student teams to the HapConnect and giving them time to experiment with its functionality. Teams were given the same challenge of navigating a maze as the ideation session, but instead supplied with the HapConnect to use as their medium of haptic communication. Taking advantage of the interchangeable snap-fit components, teams were allowed to choose the number and orientations of the actuators to satisfy the project requirements. While testing their theories and configurations, a sample maze (see Figure 4) was provided for use without any sensory constraints being applied. Each team's HapConnect orientations were recorded on the end of the third day, as well as their justification for potential success in the maze.

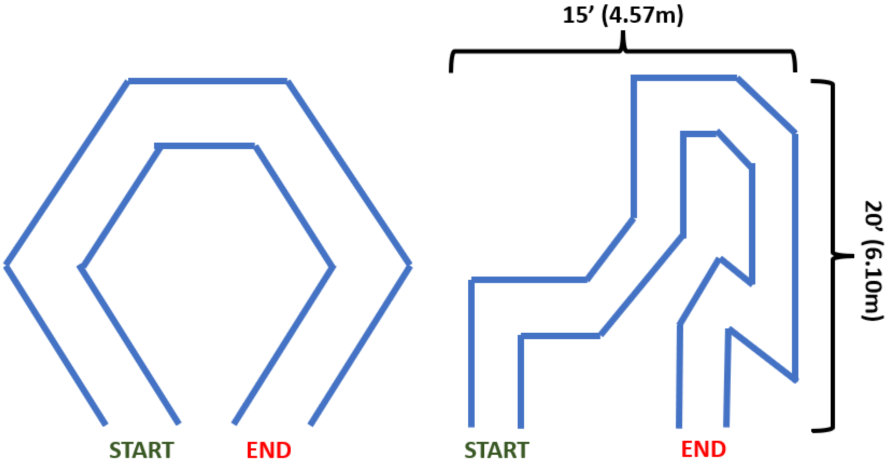

Figure 4: Sample testing maze (left) and randomly generated, final project maze (right) for students using the HapConnect

On the fourth and final day, student teams selected a person from the team to be the controller and navigator for the maze. The controller was in charge of triggering the haptic feedback to guide the navigator through the maze. The HapConnect was then constructed using the team's final design choice, while the navigator donned a blindfold and noise-canceling headphones. Teams were then brought into the testing room and shown the final maze for the first time. All students except for the navigator could see the outline of the maze, but could not interact with the navigator beyond taking them to the starting point.

Figure 5: Students utilizing the HapConnect device during the final testing day to navigate through a mapped floor maze, all while blindfolded and wearing noise canceling headphones

If the navigator accidentally stepped out of the maze, the last remaining student team member would tap them as an indication to take one step backwards from their current path. Recorded values included the time for successful maze completion, as well as the number of boundary penalties each team incurred. The task was judged by two engineering faculty members to whom the team would demonstrate their HapConnect designs and provide justification of their design choices.

4. Methods

Before introducing the lecture portion of the module, students were given a pre-questionnaire to assess their current understanding of the topics that would be discussed throughout. This same grouping of questions was asked again in the first section of a post-questionnaire in order to compare the perceived learning and learning confidence levels of students after participating in the module. The pre-questionnaire and first section of the post-test questionnaire were as follows, with corresponding keyword tags:

Q1 [Haptics]. What is haptics?

Q2 [Confidence]. How confident do you feel about the previous answer? (Likert Scale)

Q3 [Parameter]. Describe how the changes in the parameters of vibration signals (e.g. frequency and intensity) can change a user's experience.
Q4 [UX]. Describe how vibration can be used to enhance user experiences in technology.
Q5 [Begin]. What factors do you consider at the beginning of the design process?
Q6 [Inclusive]. What does it mean to be inclusive as a designer?
Q7 [Coms]. List two different ways you could convey information or communicate to a user through a technological design.

Following the completion of the module, students were asked to complete a post-questionnaire consisting of the same original questions from the pre-questionnaire (Q1-Q7), and an additional mix of free response (Q8-Q13) and rated scale response (Q14-Q20). This second questionnaire was intended to gather data on the extent in which students learned about haptics and inclusive design from the module, as well as feedback on the design and functionality of the HapConnect. These additional questions are as follows:

Q8 [Challenge]. What did you find most challenging about the activity?
Q9 [Reward]. What did you find most rewarding about the activity?
Q10 [Change]. In what ways did your design change over the course of the activity?
Q11 [Future]. Would you apply the knowledge gained from this activity to future projects, inside or outside the classroom? Why or why not?
Q12 [Lecture]. What was most useful about the lecture component?
Q13 [Project]. What was most useful about the project component?
Q14 [Improve]. Are there any improvements you would make to any part of the activity?
Q15 [Use]. The device was easy to use.
Q16 [Customize]. The device was easy to customize.
Q17 [Deliverable]. The device affected your ability to meet the project deliverable.
Q18 [LearnHap]. The device affected your learning of haptics.
Q19 [LearnInc]. The device affected your learning of inclusive design principles.
Q20 [Interest]. The device affected your interest in non-traditional engineering fields.

5. Results and Discussion

The research questions for this project were (1) how using a customizable, haptic wearable device increased student understanding of haptics and inclusive design practices, and (2) how separate student teams design their devices differently for their final day deliverable. Investigational Question (1) will be primarily addressed by analyses of the pre- and post-questionnaires. Question (2) will be addressed in the analysis of team design choices under device performance metrics. The following sections split the questions from pre- and post-questionnaires into two categories: qualitative analysis of learning (Section 5.1) and quantitative analysis of the HapConnect (Section 5.2).

5.1 Pre- and Post-Questionnaire Analyses (Qualitative)

The first analysis was on how student understanding of haptics and inclusive design practices changed before and after participating in the module. To answer this, Q1 and Q2 of the pre- and post-questionnaires were used to interpret perceived student confidence of the topics. When asked Q1, “What is haptics?”, on the pre-questionnaire, 14.7% of students were unsure of what it entailed and there were numerous qualitative themes identified. Themes were based on the student’s word choice and general response topic, and could also have multiple themes present per response leading to a higher response total than student count. After the module, student responses narrowed and included qualitative themes of touch, vibration, technology, or communication. Responses (N=25) were recorded and grouped based on these themes to present in the Pareto charts of Figure 6.

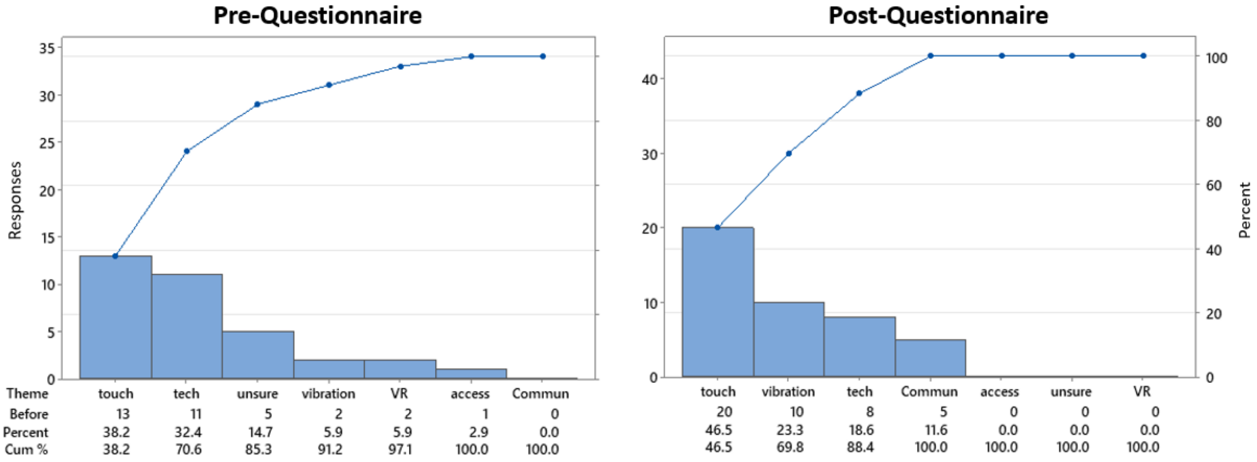

Figure 6: Example Pareto chart from Q1 of the questionnaires showing qualitative theme responses from the pre-questionnaire (left) and post-questionnaire (right)

Following the qualitative thematic analysis, a Mann-Whitney U Test was performed to determine whether the population medians of the two data groupings differed on Q2. The analysis showed the median response to the pre-questionnaire was a rating of three, a neutral response, whereas the post-questionnaire median response was five, high confidence. Under a 95% confidence interval, the data provided a p-value ≤ 0.000, demonstrating strong statistical significance with the practical standpoint being student self-confidence in their knowledge of haptics being increased dramatically. Figure 7 details a more streamlined look into student’s perceived confidence levels (from Q2) based on responses to Q1 of the questionnaires.

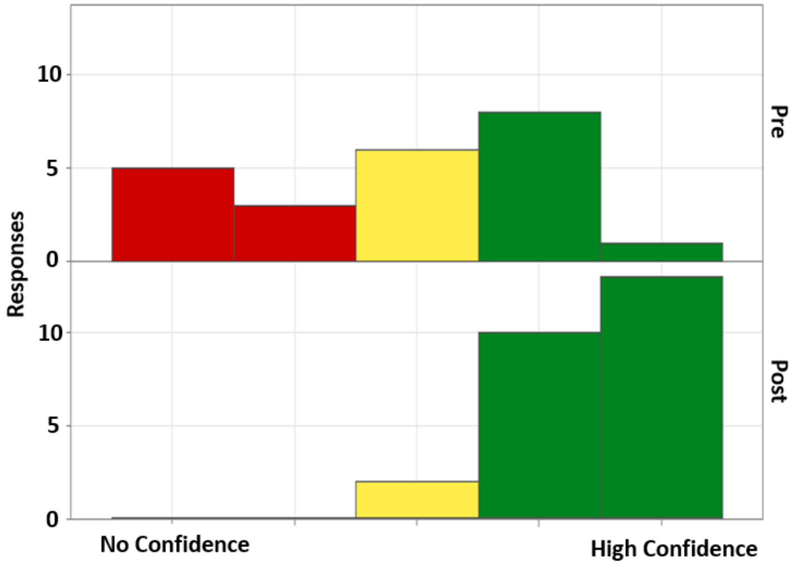

Figure 7: Student self-rated confidence in answering Q2 of the questionnaire, with the ratings from pre-questionnaire (top) and post-questionnaire (bottom)

Question	**Top Associated Themes (Response - %)**
Q8 [Challenge]	- Navigation of the maze (36%) - Deciding HapConnect layout (36%) - Differentiating sensations between motor types (16%)
Q9 [Reward]	- Satisfaction from maze results (48%) - Ability for real-time control (28%) - Application of the HapConnect (24%)
Q10 [Change]	- The system was simplified (32%) - Motors were swapped, added, or removed (24%) - Patterns were created for the motors (24%)
Q11 [Future]	- All students responded with yes with a variety of applications mentioned
Q12 [Lecture]	- Understanding haptics (36%) - Applications of haptic technologies (32%) - Understanding inclusive design (24%)
Q13 [Project]	- Understanding the hardware (44%) - Experiencing a real-life example (40%) - Applying the lecture material (12%)
Q14 [Improve]	- None (40%) - More time for the module (24%) - Allow for design of the HapConnect from scratch (24%)

Table 2: Student free response feedback from the post-questionnaire about the different components of the learning module

The remaining questions present on both questionnaires (Q3-Q7) all followed similar trends shown in Figure 7. For example, in Q3, it was observed that students were vague in their responses for the pre-questionnaire, with answers like “it changes the feeling” or “it could mean different things”. In the post-questionnaire, answers were more elaborate and had detailed descriptions, such as “evoking different feelings to communicate”, “differentiating types of movement (ex: moving speed, amount of turning)”, or “it can make it easier for users to interpret vibrations and add more variations on each type of vibration signal”. This was also illustrated in Q6 as four students responded with uncertainty in the pre-questionnaire, while the post-questionnaire had 22 responses featuring an element of human-focused design. An additional section of free response feedback was included in the post-questionnaire (Q8-Q14). Responses (N=25) were categorized by the different thematic topics described in student responses, and compiled together into Pareto chart-like summaries of just the qualitative feedback (see Table 2).

Overall, student understanding of haptics and inclusive design increased after participation in the module, as demonstrated by the responses to Q1-Q7. The application of the learning through the HapConnect also increased the desire to continue applying the principles involved in the learning module as demonstrated by responses to Q11 and Q14. High ratings from Q18-Q20 (see Table 3) further emphasize the positive learning outcomes students received from the module.

5.2 Device Performance Metrics (Quantitative)

When evaluating the final HapConnect designs, it was found that no team chose the same design and teams had unique reasoning behind the decisions for certain patterns (see Figure 8). Team 6 filled all nine rail slots and mapped different rows to the intensity of turns. They hypothesized that the vertical orientation would provide stronger intensity for greater degrees of turning, while the horizontal orientation’s “softer feel” could be used for smaller turning increments. Team 5 took a different approach and instituted a tank-drive method, with left and right vertical orientation motors being active together to signal forward movement. If only one side was active, the navigator was to turn on the spot until they felt the two motors engage together again. Compared to the complex approaches of Teams 1, 2, and 6, Team 7 simplified the design by having direction turning mapped to the left and right slots, while one single buzz of the middle motor indicated forward motion until it buzzed again to stop. Deviating from the traditional approaches of the other teams, Team 4 created a pattern system, where short motor activations were used for each step and held motor activations indicated turning on toward the direction of each respective rail. It should be noted that all motors could be activated at the same time, but student teams never used more than two at a time.

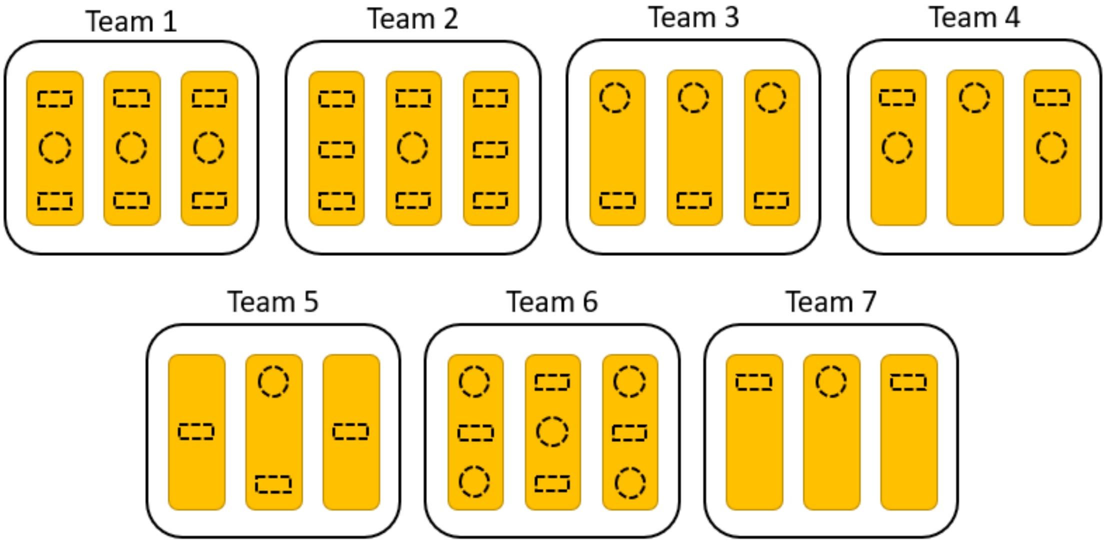

Figure 8: HapConnect arrangement patterns for the final testing day. Rectangles were vertically oriented motors, circles were horizontally oriented motors, and blank spaces were unused slots

Questions	**Responses (%)**				
	Strong Neg.	Some Neg.	Neutral	Some Pos.	Strong Pos.
Q15 [Use]	0	0	16	52	32
Q16 [Customize]	0	4	16	12	68
Q17 [Deliverable]	4	0	16	44	36
Q18 [LearnHap]	0	0	4	40	56
Q19 [LearnInc]	0	0	8	48	44
Q20 [Interest]	0	0	12	44	44

Table 3: Results from post-questionnaire quantitative feedback section detailing different aspects of the HapConnect's general functionality

All teams managed to finish in under five minutes and had minimal out-of-bounds penalty steps. The fastest team completion time was 2.16 minutes with one boundary penalty, while the slowest completion time was 4.37 minutes with four boundary penalties. The mean time was 3.35 minutes ($\sigma = 1.14$) with a mean of 1.86 boundary penalties ($\sigma = 1.12$) per team.

The final set of questionnaire analyses came from the quantitative feedback section of the post-questionnaire (Q15-Q20), with Table 3 outlining the results from this section of questions. This section was intended to garner feedback on functionality of the HapConnect through 5 point Likert scales in order to generate deeper understanding towards research question two. General consensus from the feedback was overwhelmingly positive with some small amount of neutral opinions and nearly no negative responses.

After the conclusion of the activity, students were informally asked if they had interest in continuing to learn more about haptics by expanding this project into a quarter or half semester module. All but two students responded with positive reception to the idea, many citing their desire to have more time to understand the intricacies of the HapConnect's development. Furthermore, five students from the course reached out with the intent of becoming involved in the haptics research conducted by the lab of the associated experimenters. Feedback from the professor of the course, and other final demonstration faculty judge, mirrored that of the students, with respect to increasing the time spent learning the electronics and coding for the HapConnect.

6. Conclusions and Future Work

This work designed and deployed a modular wearable haptic device in an early-level engineering design course to introduce the topics of haptic and inclusive design techniques into the classroom. This work contributes to both haptics and to engineering education through the design of the HapConnect and learning module. The modular, reconfigurable design of the wearable device is a novel feature that lowers the barrier for learners new to haptics, enabling them to begin haptic design in a simple form independently. Further, the HapConnect brings the modality of touch into the design equation, teaching early designers about the principles and importance of incorporating multimodal feedback into their innovations.

In future work, the HapConnect stands to be expanded to include other types of haptic actuation including skin stretch and pressure tapping, introducing new design and technical challenges while retaining the modularity and reconfigurable properties. The HapConnect will also be deployed in both engineering and non-engineering settings, and in conjunction with educational content designers to encourage the use of haptics more broadly. Haptics in and of itself has the ability to reshape our approach to learning, as demonstrated through this short learning module. By valuing accessibility through the inclusion of touch as a medium for communication, the field can open to more groups and foster new growth.

References

[1] C.J. Cascio, D. Moore, and F. McGlone. "Social touch and human development." *Developmental cognitive neuroscience* 35 (2019): 5-11.

[2] G. S. Giri, Y. Maddahi, and K. Zareinia. “An application-based review of haptics technology.” Robotics 10.1, 29, 2021.

[3] M. Sreelakshmi and T. D. Subash. "Haptic technology: A comprehensive review on its applications and future prospects." *Materials Today: Proceedings* 4.2 (2017): 4182-4187.

[4] R. Hadi and A. Valenzuela. "Good vibrations: Consumer responses to technology-mediated haptic feedback." *Journal of Consumer Research* 47.2 (2020): 256-271.

[5] R.F. Mulcahy, and A. Riedel. "“Going on a sensory adventure, a touchy subject?”: investigating haptic technology and consumer adventure orientation." *Journal of Service Theory and Practice* 32.1 (2022): 5-29.

[6] A.R. Licona, et al. "Applications of haptics in medicine." *Haptic Interfaces for Accessibility, Health, and Enhanced Quality of Life* (2020): 183-214.

[7] W. Benson, et al. "Embodied Expressive Gestures in Telerobots: A Tale of Two Users." *ACM Transactions on Human-Robot Interaction* (2022).

[8] A.D. Dumford and A.L. Miller. "Online learning in higher education: exploring advantages and disadvantages for engagement." *Journal of computing in higher education* 30 (2018): 452-465.

[9] B. Hannaford and A.M. Okamura. "Haptics." *Springer Handbook of Robotics* (2016): 1063-1084.

[10] F. Bara, E. Gentaz, and P. Colé. "Haptics in learning to read with children from low socio‐economic status families." *British Journal of Developmental Psychology* 25.4 (2007): 643-663.

[11] S. Reid, L. Shapiro, and G. Louw. "How haptics and drawing enhance the learning of anatomy." *Anatomical sciences education* 12.2 (2019): 164-172.

[12] J. Minogue and M.G. Jones. "Haptics in education: Exploring an untapped sensory modality." *Review of Educational Research* 76.3 (2006): 317-348.

[13] F.G. Hamza-Lup and I.A. Stanescu. "The haptic paradigm in education: Challenges and case studies." *The Internet and Higher Education* 13.1-2 (2010): 78-81.

[14] R. Crandall and E. Karadoğan. "Designing pedagogically effective haptic systems for learning: a review." *Applied Sciences* 11.14 (2021): 6245.

[15] A.M. Okamura, C. Richard, and M. R. Cutkosky. “Feeling is believing: Using a force‐feedback joystick to teach dynamic systems.” *Journal of Engineering Education* 91.3 (2002): 345-349.

[16] R.L. Davis, et al. "The haptic bridge: Towards a theory for haptic-supported learning." *Proceedings of the 2017 conference on interaction design and children*. 2017.

[17] J.L. Gorlewicz, L.B. Kratchman, and R.J. Webster III. "Haptic Paddle Enhancements and a Formal Assessment of Student Learning in System Dynamics." *Advances in Engineering Education* 4.2 (2014): n2.

[18] T.K. Morimoto, P. Blikstein, and A.M. Okamura. "[D81] Hapkit: An open-hardware haptic device for online education." *2014 IEEE Haptics Symposium (HAPTICS)*. IEEE, 2014.

[19] C.G. Rose, J.A. French, and M.K. O'Malley. "Design and characterization of a haptic paddle for dynamics education." *2014 IEEE Haptics Symposium (HAPTICS)*. IEEE, 2014.

[20] A.M. Brandt and M.B. Colton. "Toys in the classroom: LEGO MindStorms as an educational haptics platform." *2008 symposium on haptic interfaces for virtual environment and teleoperator systems*. IEEE, 2008.

[21] A.J. Silva, et al. "Phantom omni haptic device: Kinematic and manipulability." *2009 Electronics, Robotics and Automotive Mechanics Conference (CERMA)*. IEEE, 2009.

[22] J. Rodríguez, and R. Velázquez. "Haptic rendering of virtual shapes with the novint falcon." *Procedia Technology* 3 (2012): 132-138.

[23] N. Dunkelberger, et al. "Conveying language through haptics: A multi-sensory approach." *Proceedings of the 2018 ACM International Symposium on Wearable Computers*. 2018.

[24] Z. Zook, et al. "Snaptics: Low-cost open-source hardware for wearable multi-sensory haptics." *2021 IEEE World Haptics Conference (WHC)*. IEEE, 2021.

[25] Y. Jiao, et al. "A comparative study of phoneme-and word-based learning of English words presented to the skin." *Haptics: Science, Technology, and Applications: 11th International Conference, EuroHaptics 2018, Pisa, Italy, June 13-16, 2018, Proceedings, Part II 11*. Springer International Publishing, 2018.

[26] K. Bark, et al. "Effects of vibrotactile feedback on human learning of arm motions." *IEEE Transactions on Neural Systems and Rehabilitation Engineering* 23.1 (2014): 51-63.

[27] A. Alahakone and A. Senanayake. "Vibrotactile feedback systems: Current trends in rehabilitation, sports and information display." *2009 IEEE/ASME International Conference on Advanced Intelligent Mechatronics*. IEEE, 2009.

[28] N.W. Moon, P.MA. Baker, and K. Goughnour. "Designing wearable technologies for users with disabilities: Accessibility, usability, and connectivity factors." *Journal of Rehabilitation and Assistive Technologies Engineering* 6 (2019): 2055668319862137.

[29] R. Espinosa-Castañeda and H.I. Medellín-Castillo. "Virtual haptic perception as an educational assistive technology: A case study in inclusive education." *IEEE Transactions on Haptics* 14.1 (2020): 152-160.

[30] J.L. Tennison and J.L. Gorlewicz. "Toward non-visual graphics representations on vibratory touchscreens: Shape exploration and identification." *Haptics: Perception, Devices, Control, and Applications: 10th International Conference, EuroHaptics 2016, London, UK, July 4-7, 2016, Proceedings, Part II 10*. Springer International Publishing, 2016.

[31] J.L. Toennies, et al. "Toward haptic/aural touchscreen display of graphical mathematics for the education of blind students." *2011 IEEE World Haptics Conference*. IEEE, 2011.

[32] W. Yu, R. Ramloll, and S. Brewster. "Haptic graphs for blind computer users." *Haptic Human-Computer Interaction: First International Workshop Glasgow, UK, August 31—September 1, 2000 Proceedings*. Berlin, Heidelberg: Springer Berlin Heidelberg, 2001.

[33] S.G. Lambert, et al. "A tangible manipulative for inclusive quadrilateral learning." *Journal on technology and persons with disabilities* 10 (2022).

[34] G. Huisman, et al. "The TaSSt: Tactile sleeve for social touch." *2013 World Haptics Conference (WHC)*. IEEE, 2013.