Haptics: The Science of Touch As a Foundational Pathway to Precision Education and Assessment

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Abstract

Clinical touch is the cornerstone of the doctor-patient relationship and can impact patient experience and outcomes. In the current era, driven by an ever-increasing infusion of point-of-care technologies, physical exam skills have become undervalued. Moreover, touch and hands-on skills have been difficult to teach due to inaccurate assessments and difficulty with learning transfer through observation. In this article, the authors argue that haptics, the science of touch, provides a unique opportunity to explore new pathways to facilitate touch training. Furthermore, haptics can dramatically increase the density of touch-based assessments without increasing human rater burden—essential for realizing precision assessment. The science of haptics is reviewed, including the benefits of using haptics-informed language for objective structured clinical examinations. The authors describe how haptic devices and haptic language have and can be used to facilitate learning, communication, documentation and a much-needed reinvigoration of physical examination, and touch excellence at the point of care. The synergy of haptic devices, artificial intelligence, and virtual reality environments are discussed. The authors conclude with challenges of scaling haptic technology in medical education, such as cost and translational needs, and opportunities to achieve wider adoption of this transformative approach to precision education.

An essential goal of precision education is to drive better patient outcomes.[1,2] Patient outcomes are highly dependent on a broad range of interrelated clinical skills including touch. Physicians use touch regularly when interacting with patients. Clinical touch can be diagnostic, such as palpation and detection of thyroid nodules or breast masses, or it can be therapeutic, such as reducing a dislocated shoulder or repairing a hernia.

Touch used by an expert physician can be difficult to communicate accurately and completely.[3] For a trainee, determining the right level of touch can take a prolonged period of trial and error due to limitations in accurate assessment and feedback on touch performance in the clinical setting. In addition to difficulties in learning transfer and accurate assessments of clinical touch, deterioration of previously learned physical examination skills has been observed during internship. This may reflect contemporary practice patterns, which deprioritize the physical examination.[4] Moreover, there is a persistent sentiment that physical examination is a lost art that will become obsolete in the face of major advances in diagnostic technologies.[5] Devaluing the physical examination and touch at the point of care is problematic. When touch goes wrong or is absent at the point of care, patient diagnosis and treatment outcomes are negatively affected.[6,7]

Most assessments of hands-on clinical skills use rating scales and checklists that promote structured assessments of physical examination and clinical procedural skills, but do not provide enough detail to allow for precise feedback. There is a need to find a learning approach to touch and physical examination that moves beyond our traditional human observation and apprenticeship model to an approach that is grounded in science and the future of technology.

Haptics is the science of touch and can provide a robust way to understand, characterize, and communicate the actions and observations of clinical touch. The first opportunity is haptic science, a continuously growing field, which provides a unique, scientific foundation for the language of touch and serves as an opportunity to explore for improving trainee feedback. The second opportunity is that there are a growing number of advances in haptic and virtual reality technology that can teach and assess clinical use of touch at the bedside for diagnostic and therapeutic purposes. In this article, we discuss how haptic science can provide better language to describe and assess touch and how haptic devices have and can be used to facilitate precision education through skill development and personalized assessment. Together, these uses of haptics can provide a much-needed reinvigoration of physical examination and touch excellence at the point of care.

Haptic Science: A Common Language for Precision Assessment of Touch

Haptic science provides a foundation for precision assessment of touch and hands-on clinical skills. For centuries, the use of touch in medicine has been considered an art, and individual preferences and approaches were considered acceptable. In 1987, Lederman and Klatzky published a landmark paper revealing their empirical discovery that haptic exploration involves a stereotypical set of hand gestures that is reproducible across a wide variety of age

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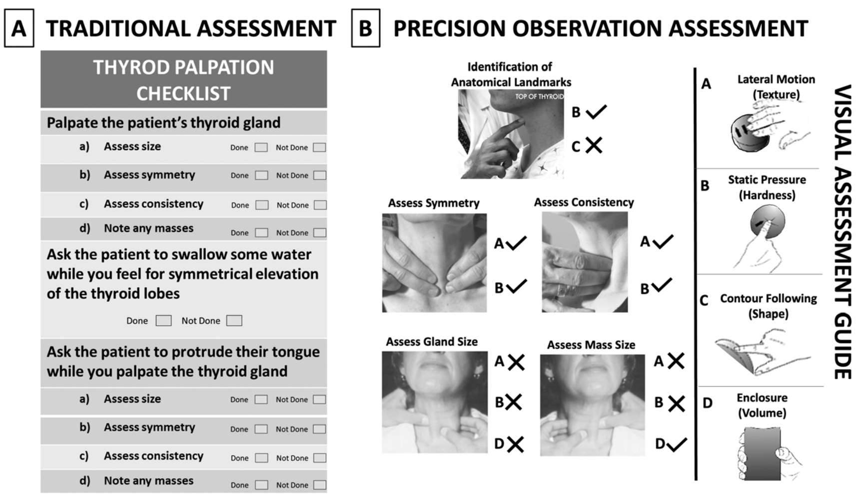

Figure 1 (A) Sample OSCE style checklist for thyroid examination compared with (B) a haptic-based assessment checklist grounded in exploratory procedures.

groups.[8] The hand gestures are called the exploratory procedures (EPs). The original EPs included 8 hand gestures and associated tactile properties including the following: lateral motion (for texture), pressure (for compliance/hardness), static contact (for temperature), enclosure (for global shape or volume), contour following (for exact shape or volume), unsupported holding (weight), part motion test (mobility), and function test (capacity and use properties).[8]

The EPs present a new language model for verbal description of hand movements that is currently not commonly used in the medical field but has clear implications for precision education. For example, consider the prototypical approach for assessing a medical student's physical examination of the thyroid gland through a checklist focused on whether each step was completed or omitted (Figure 1A).[9] The benefit of the checklist assessment is that it informs the student whether they have missed any of the procedural steps. In contrast, by adopting a new EP-enhanced language model, a haptic-based assessment of a student's thyroid examination skills will include precise, moment-to-moment feedback on the EPs the student used or omitted when examining the patient's neck. The types and combinations of hand movements used during the thyroid examination will vary based on the procedure step. Haptics can note the student's assessment of hardness, mobility, texture, and shape based on the EPs used (or omitted) during the examination. If a given student's assessment of a thyroid nodule is inaccurate, it may be linked to the omission (or inadequate use) of one the EPs.

Shifting from done/not done checklists to EP-based feedback increases the density and precision of assessment of touch during a standardized encounter. However, while use of language from haptic science is important for improving direct observation, measurement of actual performance would be desirable—both for training and assessment purposes. Haptic devices provide one possible approach.

Haptic Devices: Tools for Precise Measurement and Feedback on Touch

Touch sensations can be grouped into 2 main categories. Cutaneous or tactile touch is sensed by mechanoreceptors in the skin and includes pressure, shear, temperature, and vibration.[10] Examples of cutaneous touch include the actions used to identify a mass on physical exam or distinguish a benign cyst from a malignancy. Kinesthetic touch is sensed in the muscles, tendons, and joints and includes forces and torques.[10] An example of kinesthetic touch is the use of motor modulation to make sure the appropriate amount of force is applied to reduce a fractured radius and ulna.

The integration of haptic feedback for medical education can take many forms. Studies of human sensorimotor adaptation support error-based learning (learning achieved by allowing the trainee to make errors and correct them) combined with use-dependent learning (learning achieved by guiding the hand of the trainee to correctly complete the task).[11] These allow the trainee to feel expert force to help facilitate an understanding of task execution. In this use-dependent mode, the haptic device could also be used for assessment by providing error correction when inappropriate force is applied, thus enabling a combination of use-dependent and error-based learning. Figure 2 provides an example of how haptic feedback could be used to augment the "see-one, do-one, teach-one" model, which is grounded in observation-based learning. Overall, there needs to be a finely tuned balance between allowing exploration and error feedback versus

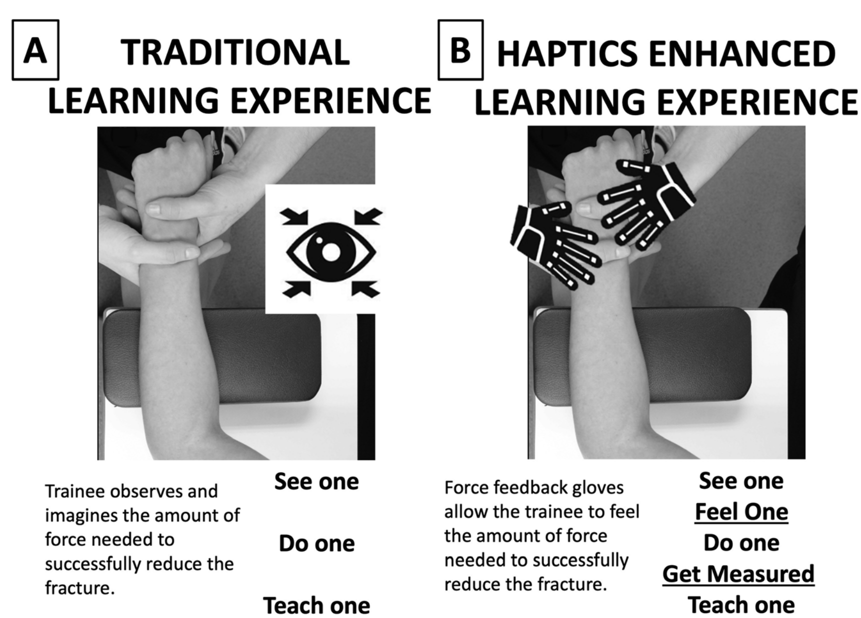

Figure 2 An example of a traditional (A) and haptic-enhanced (B) learning experience during a wrist fracture reduction performed at the point of care.

guiding the learner to follow a certain prescribed path.

Haptic devices are tools that can recreate and/or measure haptic interactions. There are 3 main categories: holdable, wearable, and touchable (Figure 3).[10] *Holdable* haptic systems are relevant to medical procedures in which one simulates grasping a medical instrument by holding and maneuvering a haptic device and receives force feedback through that haptic device. Holdable systems provide feedback directly at the point of action. In Figure 2A, the user is using a movable haptic tool to "feel" a virtual lamp.

Wearable haptic devices provide force or tactile feedback in cases where grasping a haptic device is not feasible or desirable as it is not part of the virtual training system. Wearable devices may vibrate or locally deform the user's skin, giving the perception of interacting with solid objects in the virtual environment. This approach can also be used to provide feedback on a part of the body not directly involved in the task.[12] In Figure 2B, the user is able to navigate a virtual world and "feel" the texture on a virtual vase. In Figure 2C, the user is able to move a robotic arm by moving their arm, which is instrumented with a haptic wearable device.

Touchable haptic interfaces allow users to interact with virtual objects in an augmented reality environment. This can provide the most realistic form of haptic feedback because the device configures its shape and mechanical properties such that the user can reach out to touch and interact directly with their fingers.[13] In Figure 2D, the user is palpating a simulated mass that can change tissue properties (size, shape, hardness). This capability can be useful in precision training of mass detection and characterization.

Within health care, kinesthetic feedback devices have been developed and used in rehabilitation to help retrain motor patterns after a stroke or neuromotor deficit. Haptic interfaces have been developed and utilized to enhance motor control of artificial limbs. In addition, haptic interfaces have been developed with the goal of enhancing the surgeon's interaction with tissue during telerobotic surgery.[10,14,15] In medical education, haptic devices enhance realism in virtual reality and manikin simulations to improve learning and provide a way to objectively quantify performance for individualized feedback.

Example use cases of haptic learning technologies for procedural care

The use of holdable devices has been well established in medical education. Typically, these devices provide kinesthetic (force) feedback with a simulated instrument. One example of the use of holdable haptics is a drill held by the participant during a simulated orthopedic procedure. Here a haptic enabled drill can provide feedback to better recreate the sensation of drilling a bone. When used in a virtual reality setting for training junior surgeons, use of the haptic enabled drill resulted in higher Objective Structured Assessment of Technical Skills (OSATS) when compared with participants who trained in simulation without haptics.[16] Another example is the laparoscopic instruments held during a simulated suturing task. In this setting, the use of haptics helped students to achieve proficiency 32% faster than students learning without haptics.[17]

Additionally, these holdable devices can be used in assessment. In these settings, the holdable device objectively quantifies haptic interactions (i.e., force applied during simulated tasks). During an endovascular navigation task where participants manipulated a guidewire to traverse a simulated aorta, assessment of force was able to distinguish between experts and novices.[18] Force-based metrics have also been used to distinguish levels of expertise in minimally invasive surgery.[19] This ability to objectively quantify performance through haptic-based tracking also allows for the use of automation and machine learning to decrease the need for human raters.[20] Enabling automated assessment would allow learners increase access to feedback to help improve their performance.

The use of wearable and touchable haptic systems has not been as widely reported in the medical literature. As a result, these systems represent an opportunity for new avenues for future endeavors in precision education and assessment. Existing consumer products such as smart watches provide haptic feedback to alternative body locations like the wrist. From a training perspective, it is easiest to interpret haptic feedback when one can actively and freely explore the virtual environment without the wearable interfering.[8] Touchable devices are often technically difficult to implement, and some provide limited interaction (Figure 3B). The design of haptic devices for improving medical education must consider the need for trainees to learn to use active touch, thus necessitating

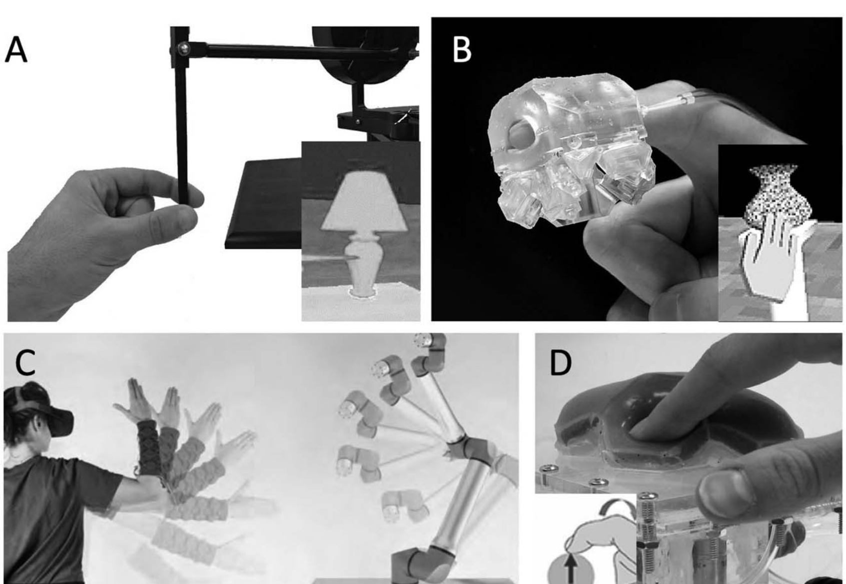

Figure 3 Examples of (A) holdable, (B, C) wearable, and (D) touchable haptic systems with sample visual interfaces. These 3 categories describe the breadth of interaction modalities for kinesthetic and cutaneous stimulation in interactive haptic devices. (Image credits: Nick Colonnese, Zhenishbek Zhakypov, Cosima du Pasquier, Susan Williams, and Andrew Stanley.)

real-time haptic feedback to the user's motions and/or applied forces.

Opportunities for haptic learning with AR/VR technology

Another opportunity is the use of haptic feedback for training in virtual or augmented reality environments. The combination of haptics with virtual environments has recently seen a major uptick in utility as head-mounted displays and handheld controllers have become widely available, less expensive, and well integrated into the virtual world. Depending on the learning goals, some of the computer-generated learning environments are realistic (i.e., models of kitchens, medical clinics, or operating rooms), and some are more abstract (or curated), like a room full of oversized blocks and triangles. From a learning perspective, the range of learner interaction and engagement is similar to the difference between watching a video of a surgical procedure versus looking at a medical illustration of a surgical procedure. Both environments offer different learning and feedback opportunities. Multimodal feedback that combines vision, sound, and haptics is thought to be the most effective for learning.[21]

The Visual-Auditory-Kinesthetic (VAK) test can help learners understand their conscious and unconscious learning needs and preferences for communicating and receiving knowledge.[22] Kinesthetic learners stand to benefit greatly from haptic devices geared toward teaching haptic approaches for hands-on clinical examinations and procedures. For visual and auditory learners learning haptic skills, virtual worlds can preferentially exploit visual or auditory information exchange blended with the haptic learning.[22] The flexibility of virtual worlds combined with haptics allows for unprecedented personalization of information and learning environments and can greatly facilitate learning and assessment, which are the cornerstones of precision education.

Summary

Haptic science and haptic devices offer tremendous potential for precision education and assessment. Using haptic science, such as EPs, as a framework for data analysis will facilitate understanding and characterizing clinical touch in a theoretically and empirically grounded fashion. The language of haptics provides a framework for revisiting proctored assessments of clinical skills.

We have presented use cases for the utility of haptic devices and application of haptic science to the assessment and training of touch in clinical care. Haptics can address the growing marginalization of physical examination as part of the workup and assessment of patients and improve training and feedback in hands-on skills. Moreover, haptic technology has experienced continued growth in the past decade, making access to virtual worlds and augmented reality a real opportunity for flexible learning environments when assessing hands-on skills. The language of haptics provides a framework for revisiting proctored assessments of clinical skills. The current rating scales and checklists, while useful, can be greatly improved with a new layer of information, language, and structure that promotes precision observation and detailed, actionable feedback for hands-on skills.

Using haptic devices offers an opportunity for more learning of hands-on skills and for dramatically increasing the density of touch-based assessments without increasing human rater burden. Haptic technology has a wide variety of capabilities that may facilitate an increased assessment of hands-on skills and physical examination, which is especially critical given the growing marginalization of such skills.[4] As discussed by Kinnear et al, such technology will enable a new epoch of technology-assisted precision assessment where each individual's fundamental, irreducible skills are measured.[23] Major League Baseball has shifted from measuring a pitcher's strikeouts to measuring each pitch's spin rate, velocity, and other granular measures. Similarly, with the use of haptic technology, medical education may soon shift from a supervisor's assessment of trainee entrustability abdominal closure to stitch-level force and movement-based measures that are linked to suture placement quality and eventually patient outcomes (as one example).

Moreover, haptic technology has experienced continued growth in the past decade, making access to VR/AR environments a real opportunity for flexible learning environments when assessing hands-on skills. While holdable haptic devices predominate in medicine, wearable and touchable haptic systems may represent an untapped opportunity for new precision education and assessment approaches.

There are several limitations to the application of haptic technology for precision learning. Access and cost are known barriers; however, as the consumer support and interest in this space grow, costs will continue to decrease. Increased availability of inexpensive AR-VR headsets has driven renewed interest in haptic interface devices especially in the holdable haptic space. Wearable and touchable haptic interfaces are not far behind in the newfound excitement relating to AR-VR technology; hence, greater availability of affordable systems is expected. The initial translation (*haptic science to bedside and precision assessment*) and implementation will be onerous. Simulation laboratories with multicamera systems for human-based observation and feedback serve as major, preexisting infrastructure resources to help build procedural databases that can be used to train machine learning algorithms how to capture and assess hands-on procedures. One of the limiting factors in training ML algorithms is the laborious and inaccurate process of human annotation. Use of the haptic EPs to guide video annotation for AI processing is a major opportunity to help us achieve our goals for precision measurements using advanced haptic technologies and approaches.

While transdisciplinary work and collaboration with engineers are happening (such as this paper), major silos still exist and the medical profession will need to continue to foster, support, and reward new collaborations. In addition, while there have been advancements in the use of AI and computer vision to auto-segment surgical procedures using large surgical video databases, this work has not translated widely into AI-enabled video-based assessments of bedside procedure and physical examination skills. Computer vision is more facile than human observation at serially tracking the wide variety of haptic EPs used during a clinical examination. Accurate tracking combined with time series and time quantification metrics will help to provide highly precise assessments of haptic performance. This is one example of many transdisciplinary processes (i.e., medicine, engineering, and haptic science) that can facilitate precision education.

When we look at future possibilities for haptic science in precision education, there are at least 2 areas that hold great promise. The first area relates to using haptics as a framework for data analysis and data analytic strategies that will enable us to better understand and characterize clinical touch. Low hanging fruit relates to advancing our rating scales and checklists with haptic language models that add structure and details for measuring hands-on performance at the point of care. The second area relates to use of haptic devices to facilitate training of hands-on skills by complementing student observations with an opportunity to feel how certain maneuvers are performed and to use the same devices to measure and auto-document hands-on performance.

Conclusions

Realizing precision education in the domain of touch will require new approaches for efficiently gathering precise, high-density data about trainees for assessment and feedback on key touch-dependent skills, such as the physical exam and procedures. Haptics, the science of touch, provides a robust body of science relating to touch that could enable evidence-informed research, curriculum development, and learning—acting as a pathway to precision education. Once we develop, adopt, and implement strategies that are valid and reliable, we will make significant progress toward applying haptic science to enhance human performance through detailed and actionable feedback. The dream of precision education is heavily dependent on seamless and efficient access to value-added information and having data streams that are structured and based on science. Haptics, the science of touch, will enable everyone to participate in research, curriculum development, and learner assessments by starting with a well-known, well-respected body of science relating to touch. This is the opportunity for the use of haptic science as a pathway to precision education.

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