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Haptic Technology Interaction Framework in Engineering Learning: A Taxonomical Conceptualization

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ABSTRACT

Innovative technology helps students foster creative thinking and problem-solving abilities by augmenting human sensing and enriching input and output information. New technology can incorporate haptic sensing features—a sensing modality for user operations. Learning with haptic sensing features promises new ways to master cognitive and motor skills and higher-order cognitive reasoning tasks (e.g., decision-making and problem-solving). This study conceptualizes haptic technology within the human-technology interaction (HTI) framework. It aims to investigate the components of haptic systems to define their impact on learning and facilitate understanding of haptic technology, including application development to ease entry barriers for educators. The research builds a haptic HTI framework based on a systematic literature review on haptic applications in engineering learning over the last two decades. The review utilizes the SALSA methodology to analyze relevant studies comprehensively. The framework outcome is a haptic HTI taxonomy to build visual representations of the explicit connection between the taxonomy components and practical educational applications (by means of heatmaps). The approach led to a robust conceptualization of HTI into a taxonomy—a structured framework encompassing categories for interaction modalities, immersive technologies, and learning methodologies in engineering education. The model assists in understanding how haptic feedback can be utilized in learning with technology experiences. Applying haptic technology in engineering education includes mastering fundamental science concepts and creating customized haptic prototypes for engineering processes. A growing trend focuses on wearable haptics, such as gloves and vests, which involve kinesthetic movement, fine motor skills, and spatial awareness—all fostering spatial and temporal cognitive abilities (the ability to effectively manage and comprehend significant amounts of *spatial* (how design components or resources are related to one another in the 3D space) and *temporal* (the logic in a process, such as the order, sequences, and hierarchies of the resources information). The haptic human-technology interaction (H-HTI) framework guides future research in developing cognitive reasoning through H-HTI, unlocking new frontiers in engineering education.

1 | Introduction

Modern advancements in educational technologies have the growing potential to simplify teaching and learning [1]. There is a new generation of technologies aimed at augmenting human senses for learning that promises to impact the development of 21st-century skills. Empowering human senses with technologies can enrich sensory input (vision, hearing, olfaction, and touch) that will benefit learners' visual, analytical, and creative skills, including the ability to exercise logic, discern judgment, and solve problems [2]. Examples of these technologies encompassed within the umbrella term "extended reality" (XR) include virtual reality (VR), augmented reality (AR), and mixed reality (MR). Multiple applications in STEM disciplines demonstrate the benefits of knowledge retention and increased student motivation and engagement compared with traditional learning methods. For example, see a summary of the broad approaches to VR-based learning in the architecture, engineering, and construction (AEC) discipline [3].

XR technologies have undergone significant improvements in recent years, particularly in terms of their hardware and software capabilities that contributed to human-computer interaction (HCI is an interdisciplinary field that draws upon a range of disciplines, such as computer science, cognitive science, and human-factors engineering, to optimize interactions between humans and technology) [4, 5]. As a development of HCI, XR presents a novel platform for developing more intuitive, efficient, and engaging interfaces [5, 6]. Furthermore, the integration of haptic feedback into XR technology can facilitate a multisensory learning experience that has the potential to enhance significantly STEM education [7].

Haptics provides users with cues through touch-based sensations, making technology more intuitive and engaging. Various haptic technologies—from smartphone touchscreens to smartwatches, joysticks, game controllers, and haptic gloves—enrich the user experience in a wide range of widespread applications, such as healthcare, gaming, and robotics [8]. For instance, haptic technology enables the exchange of touch-based information between humans and computer interfaces [9]. Using haptics opens up the possibility of expanding humans' capabilities in various ways, such as increasing physical strength, improving manual dexterity, and augmenting and sensing [10].

The broad range of applications and the transformative impact of haptic technology on HCI highlights its potential for enhancing education, particularly in STEM fields. Haptic technology can bridge the gap between abstract concepts and tangible experiences, making learning more immersive and effective. Given the technology capability to stimulate haptic sense and provide rich sensory feedback, there is strong motivation to explore how this technology application can be effectively integrated into STEM education to improve and enhance learning experiences.

The structure of this paper has an introduction, background, methodology, discussion, conclusions, acknowledgments section, and appendix. The latter section discusses the most salient or significant concepts from the haptic human-technology interaction (H-HTI) taxonomy, the impact of the trends of haptics in learning, and the constraints and potential sources of bias inherent to this research effort.

2 | Background

Early research about haptics applications for STEM learning focused on developing and evaluating haptic devices and interfaces, exploring the use of haptic feedback in basic tasks, and investigating the haptics potential for improving spatial awareness and visualization skills. The studies focused on how haptic technology was applied to learning to simulate physical conditions by providing kinesthetic information, such as force, vibration, and motion [11, 12]. Initial haptic implementations included manipulations with digital models in a 3D virtual environment [13] and shaping tools in 3D through force measurements from a robot machining system [14]. For example, interventions of haptics for teaching engineering and programming concepts involved interfaces created with LEGO MindStorms [15] and novel methods for rapid product development based on haptic modeling [16]. Tsunashima and Katsura [17] suggested a motion-copying system named "spatio-temporal coupler" that allowed the acquisition, preservation, and reproduction of human motions regarding haptic information. Strohmeier and Hornbæk [18] proposed generating textures using vibrotactile feedback relative to the user's motion. Also, a widespread haptic invention for learning, "Hapkit," was designed as a low-cost, open-source kinesthetic haptic device for educational applications [19]. Other recent research has primarily focused on incorporating haptic feedback in autonomous robots. For instance, Seminara et al. [20] proposed a functional hand- or finger-based robotic control scheme in a closed-loop sensorimotor system.

More advanced haptics interventions in engineering learning were developed for the healthcare industry that included haptic simulations in virtual environments, such as multiple applications of "The da Vinci Research Kit" for robot-assisted minimally invasive surgery presented in a comprehensive review by D'Ettorre et al. [21].

In the fields of AEC, Medellín-Castillo et al. [22] discussed the Haptic Assembly and Manufacturing System (HAMS), which can replicate assembly tasks of complex components with force feedback provided by the haptic device "Phantom Omni." In addition, Ranjith et al. [23] presented a customized educational toolkit that utilizes vibrotactile technology to enhance realism and encourage skill development during vocational training for construction personnel, such as carpenters, plumbers, and masons. Likewise, several studies were dedicated to augmenting actual hands-on conventional training methods of soldering and carpentry skills with haptic simulations in VR as part of computer-based vocational training [24, 25].

The current focus of research on haptics in AEC is to enhance the interaction between humans and machines by developing more sophisticated haptic devices and techniques. It includes developing haptic feedback systems for MR, haptic interfaces for teleoperation and telepresence, and integrating haptic technology into autonomous systems. Among recent studies, a remote operation of construction robots through VR and haptics was studied by Adami et al. [26]. The learner's ability to coordinate systematically and understand a broad spectrum of engineering systems is crucial in AEC, especially in managing and scheduling construction activities on site. Essentially, haptic interventions affect activities that require detailed observation of the construction in the spatiotemporal context [27].

From the STEM education perspective, researchers examine how haptic technology can refine various aspects of the learning process, such as enhancing student engagement, promoting conceptual understanding, and facilitating skill acquisition. In particular, several authors have demonstrated the advantages of haptic feedback for improving the quality of interactions and spatial guidance. For instance, augmenting VR with haptic feedback enhances overall task performance and the users' perceived sense of presence [28]. Other experimentations claim that haptic feedback decreases the execution time and proportion of failed attempts compared with visual feedback [29]. Others explored physical interaction and experiences by coordinating touch sensation, perception, and movement [30]. Finally, one of the latest cutting-edge immersive technologies—holoportation—enables the capture and transmission of high-quality 3D images from one place to another and utilizes holograms accompanied by haptic devices that can be applied to online education and remote communication [10].

Overall, considering XR as a fast-evolving technology for learning, haptics should be reviewed comprehensively by clustering haptic modalities into one structure to increase the efficiency of prototyping haptic features.

Over the years, researchers have attempted to classify haptic devices and their features based on various domains, such as training, robotics, entertainment, rehabilitation, and others. For example, Azofeifa et al. [31] conducted a systematic literature search of multimodal HCI that encompasses interaction technologies of VR and haptics for different concepts, human factors, and user experience designs. Likewise, Crandall and Karadoğan [32] summarized the best design practices of haptic simulations and their pedagogical applications in various fields.

The most extensive taxonomies for the design of haptic systems were developed by Kern et al. [33], who proposed various classifications of perceptual properties of haptics, along with technological solutions for task-specific haptic systems. Additionally, a comprehensive overview of smart wearables, including various haptic gadgets, was presented [34, 35]. Moreover, a taxonomy of haptic devices based on their wearability level was proposed by reviewing papers from 2010 to 2021. There were also several specific taxonomies for the haptic elastic displays [36] and encountered-type haptic displays [37].

In recent studies, human haptics has been clustered in the context of robotics, such as categorizing haptic feedback systems for microrobotic [38] and taxonomy for a closed-loop sensorimotor robotic control by hands and fingers [20].

2.1 | Research Gap

While the potential of haptic technology to improve learning is acknowledged, there are still several significant limitations in the current research, especially regarding its application in education. Research on haptics is often fragmented, focusing on specific applications—such as medical training or robotics—rather than providing a generalized approach suitable for broader educational contexts, particularly engineering education.

Current taxonomies of haptic technology provide valuable contributions, primarily by categorizing technology devices based on their design features, application domains, or perceptual properties. However, these research efforts do not effectively address educational applications, especially in establishing a cohesive framework for incorporating haptic feedback to enhance learning. The taxonomical classifications are predominantly focused on technical and domain-specific attributes rather than learning objectives, which limits their applicability in an educational context.

The current taxonomies also need to encompass the broader human-technology interaction (HTI) process from a learning perspective. They do not consider how various haptic technologies can be aligned with different educational goals, nor do they explore how haptic feedback can facilitate the development of specific skills—such as problem-solving, critical thinking, and specific engineering competencies.

More research is needed to evaluate the impact of haptic feedback on learning outcomes. One example is research measuring how haptic technology enhances learning and its incorporation into curricula. Investigating these issues can reduce the high costs and technical complexities that challenge the scalability of haptic solutions—such challenges hinder their widespread use and significantly affect underfunded educational institutions.

The gaps in the current taxonomies highlight the need for a comprehensive framework designed explicitly for educational contexts. The presented taxonomy bridges the research gap by categorizing haptic technology based on its pedagogical value, potential learning outcomes, and adaptability to diverse learning environments. Such a framework would guide the development of effective haptic interfaces that could seamlessly be integrated into educational curricula, particularly in engineering education, where multisensory feedback is vital for developing practical skills. It would also help educators and designers create personalized learning experiences that cater to different learner profiles, ultimately enhancing the overall effectiveness of haptic technology in education.

2.2 | Research Questions

The literature review illustrates the fragmented state of research into haptic technologies. Studies focus on individual applications or devices without considering the broader implications for learning. By developing a comprehensive taxonomy that unifies these disparate approaches, this research addresses the need for educational focus and the integration of haptic technologies in learning.

This taxonomy provides a foundation to guide the design of effective haptic interfaces explicitly tailored for educational contexts within engineering. Addressing this need is crucial, as current literature needs a holistic understanding of how haptic feedback can be systematically implemented to enhance learning outcomes, especially in engineering disciplines where practical skills and multisensory feedback are essential.

The study research questions follow.

1. *What is the status of research on haptic applications in STEM learning and the anticipated trends of developing haptics for learning?*

   This question directly builds upon the literature review, to identify the focus areas for research needs. The authors establish a basis for understanding the broader landscape of haptic technology in STEM education by identifying current trends and the scope of haptic applications.

2. *What are the potential benefits of engineering learning after integrating HTI into a framework for learning?*

   The literature points to the potential of technologies like mixed reality (XR) and haptics for enhancing student engagement and learning. This question will explore how these technologies can strengthen engineering competencies when integrated into a systematic framework.

3. *What are the challenges and limitations of the current haptic HTI for engineering learning?*

   The identified gaps in the literature—such as the lack of educational focus and the limited conceptual understanding of haptic feedback in education—form the basis for this research question. Addressing these challenges will help identify opportunities for improvement and areas that need further investigation to make haptic interfaces effective for engineering education.

2.3 | Contributions

Prior research has focused primarily on categorizing haptic applications according to the general technical characteristics of haptic technology. Due to the general focus on these taxonomies, researchers may find it challenging to understand how haptic technology can be implemented for learning based on HTI. The presented study explores the fundamental relationships between users, technology, and interactions from the learning lens. It introduces a taxonomy built from state-of-the-art haptics research as a mechanism that facilitates the analysis of the fundamental relationships. The taxonomy was built upon an analysis of a solid and systematic literature review (SLR) that examined relevant papers on haptics interventions in STEM learning over the last two decades. The analysis offers several benefits, including:

- Shedding light on research and developments of user-centered designs in learning that use haptic technology, including practical, intuitive, and accessible haptic interfaces.
- Investigating the significant components of haptic technology that enable comparison and assessment of various systems and their impact on learning, reducing development time and accelerating technology implementations.
- Easing entry barriers for course designers and adopters of learning technologies, who may not have extensive experience with haptics feedback.

In sum, considering all the potential impacts of haptic technology, this study provides notable contributions:

1. Detailed analysis of publication output on the applications of haptics in STEM for the past two decades;
2. Classification of the papers according to haptic technology integration in STEM learning;
3. Insights into the current status, benefits, challenges, and future directions of HTI and haptics in learning engineering disciplines;
4. A taxonomy, as a form of conceptualization of H-HTI that categorizes and describes interaction modalities, methods, technologies, and devices for learning, serves as a guide for researchers and practitioners in designing learning systems in engineering.

3 | Methodology

This study consisted of two phases. First, a systematic literature analysis was carried out to illustrate the progress of haptics applications as a learning tool in engineering education and engineering workforce training. The review presented the distribution of relevant articles based on temporal, geographical, and typological distributions to show the status of research in haptics quantitatively. Second, the main drivers in human-haptic technology interaction were identified and analyzed. The analysis provided information for the taxonomy formulation—a critical outcome of this study. A discussion of the key findings regarding the potential benefits and challenges of haptic technology applications for learning and teaching in STEM follows the methodology section.

The researchers followed a SLR process based on the search, appraisal, synthesis, and analysis (SALSA) framework [39]. In this framework, search defines a searching string and types of databases, appraisal predefines literature inclusion and exclusion and quality assessment criteria, and synthesis extracts. It categorizes the data and analysis and narrates the results and conclusions. The steps are shown in Figure 1.

3.1 | Search

The first step of the (SALSA) framework encompasses a set of tasks (named identification, screening, eligibility, and inclusion).

- *Identification*: The choice of search engines for data collection was based on a list of appropriate search engines and their performance criteria [40]. ScienceDirect, Web of Science, and

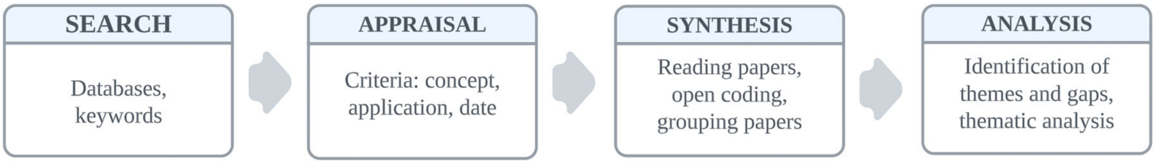

FIGURE 1 | SALSA framework for systematic studies.

Google Scholar were selected as primary databases, and IEEE Xplore as a specialized supplementary resource for the subject area. The literature search included keywords *haptic* AND *engineering* AND *education*. To ensure coverage of all aspects of the multidisciplinary research topic, a search was conducted across interconnected subject areas: Engineering, Education, Computer Science, and Multidisciplinary Sciences. The key selection criterion for articles included in the data set was a proposal for leveraging haptic technology to develop skills for executing engineering tasks.

- *Screening*: During the screening process, the database was cleaned of duplicates, irrelevant topics, inappropriate interventions, and review papers.
- *Eligibility*: Full-text screening of selected articles allowed us to remove irrelevant papers, ensuring the appropriate population of STEM learners and valid research outcomes.
- *Inclusion*: As a result of meticulous reading of full-text papers, 40 publications were selected for further research on interventions of haptics in STEM.

The outcomes of these individual tasks are summarized in Figure 2.

3.2 | Appraisal

This task is a further step for in-depth database examination. It consists of extracting publication metrics to define the chronological and geographical distribution of relevant 40 selected publications, creating bibliometric networks, and designing visual representations of the results.

The output of searches has the following distribution of subject areas (see Figure 3). From the figure, most haptic applications take place in engineering training and manufacturing. However, haptic technologies are utilized almost equally in Computer Science, Medicine and Dentistry, and Social Sciences.

For the trend in the scientific production of selected publications, Figure 4 shows an upward trend from 2000 to 2018. Between 2011 and 2019, there was a particularly steep increase in research articles on haptics. During that period, haptic technology witnessed many breakthroughs, such as creating novel haptic devices and successfully incorporating haptic feedback into virtual and AR systems. The number of related papers grew significantly in 2019, presumably due to the adaptation to the remote nature of organizing learning processes, which facilitated the development and necessity for XR technologies. In recent years, the number of research articles on haptics has continued to increase steadily, reflecting the growing importance of haptic technology in engineering.

The geographical distribution of research on haptics has been conducted in various countries worldwide, primarily with notable contributions from the United States, Japan, South Korea, China, Canada, and Germany. As shown in Figure 5, the United States takes the lead in scientific production due to a strong tradition of cutting-edge research in haptic technology and its applications, particularly in HCI, robotics, and engineering. Major universities and research institutions in the United States have active haptic research programs. Numerous companies and startups are developing and commercializing haptic technology for a wide range of applications.

The analysis of bibliometric networks of 40 selected papers performed with VOSviewer demonstrates the most frequently used keywords that are commonly used together with overlapping topics (Figure 6). The network constructed by VOSviewer consists of items (e.g., authors, publications, and keywords) and links showing a connection between the two

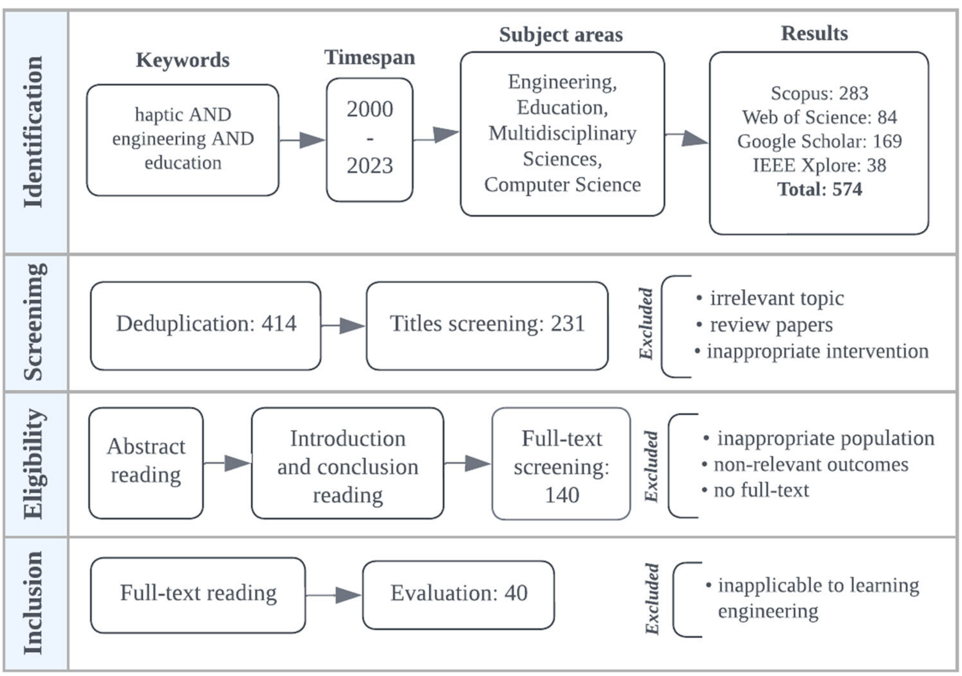

FIGURE 2 | The screening procedure for systematic records selection.

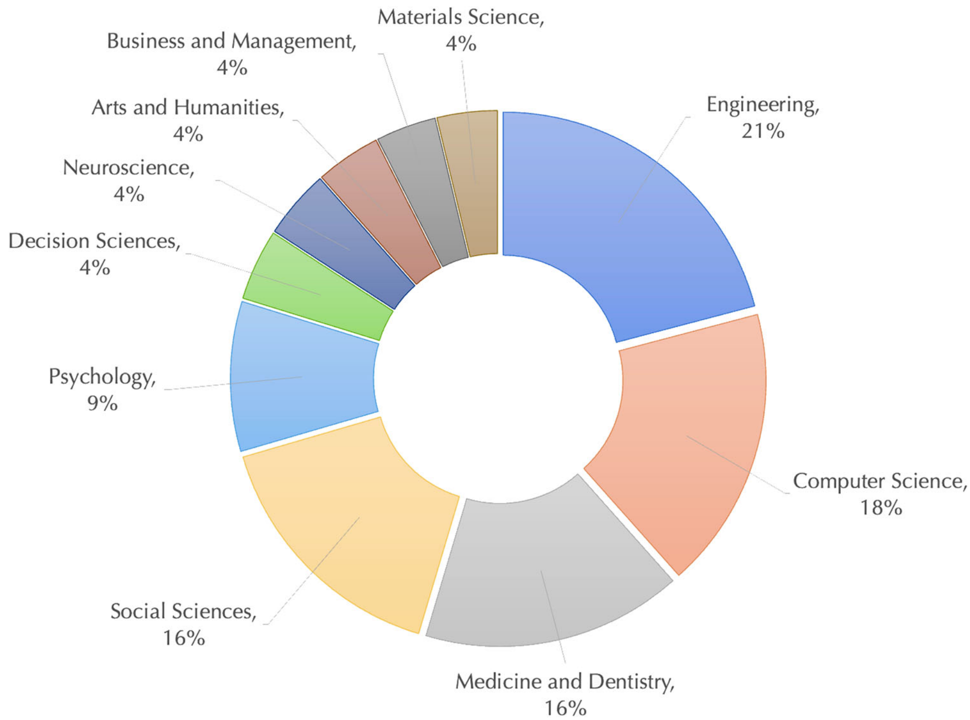

FIGURE 3 | Distribution of subject areas with haptics intervention.

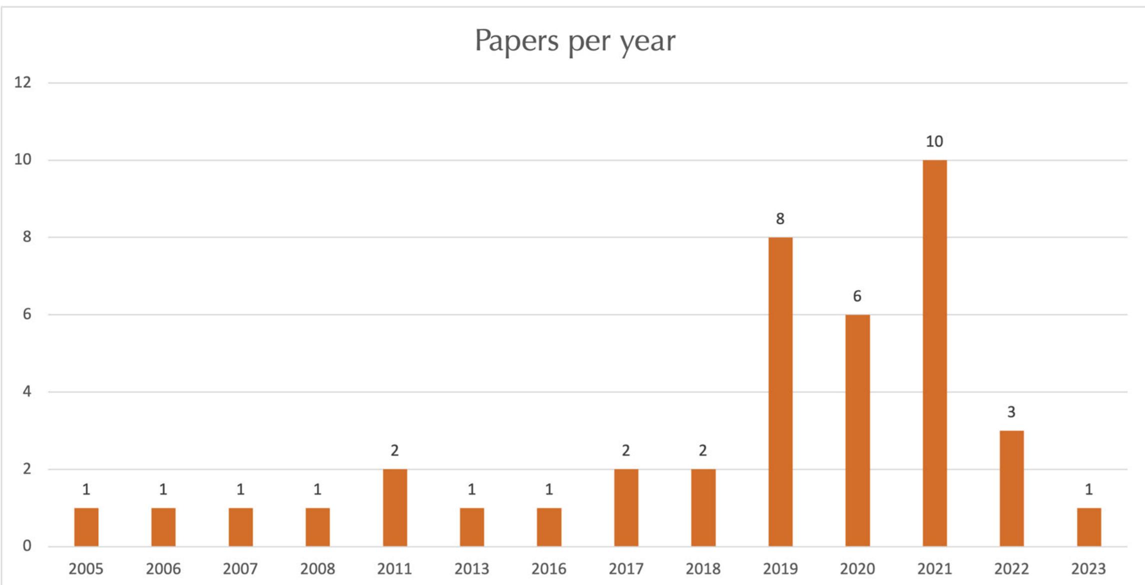

FIGURE 4 | Chronological distribution of articles on haptics interventions in STEM learning.

items. From the figure, a common characteristic of haptic applications in Engineering is virtual assembly with haptic feedback within VR environments. This outcome implies a simulation-based approach to learning and training in which users assemble virtual components using haptic devices.

For a complete understanding of the utilization of haptic devices in engineering education, it is crucial to examine their chronological distribution across various types. Figure 7 charts this trend based on the classification developed by Culbertson et al. [41], which distinguishes three main categories of haptic devices: graspable, wearable, and touchable. Graspable haptic systems are typically focused on kinesthetic feedback, although some incorporate cutaneous feedback (e.g., vibrations) through handheld tools. Touchable haptic devices are interactive displays that enable users to manipulate objects shown on the screen through vibrotactile, electrostatic, or ultrasonic feedback. Wearable haptic devices, such as haptic gloves and exoskeleton systems, are designed to deliver diverse forms of haptic feedback while attached to the user's body.

On the whole, the evolution of haptic devices from 2000 to 2023 has seen advancements in terms of feedback capabilities, wearability, precision, and integration with other XR

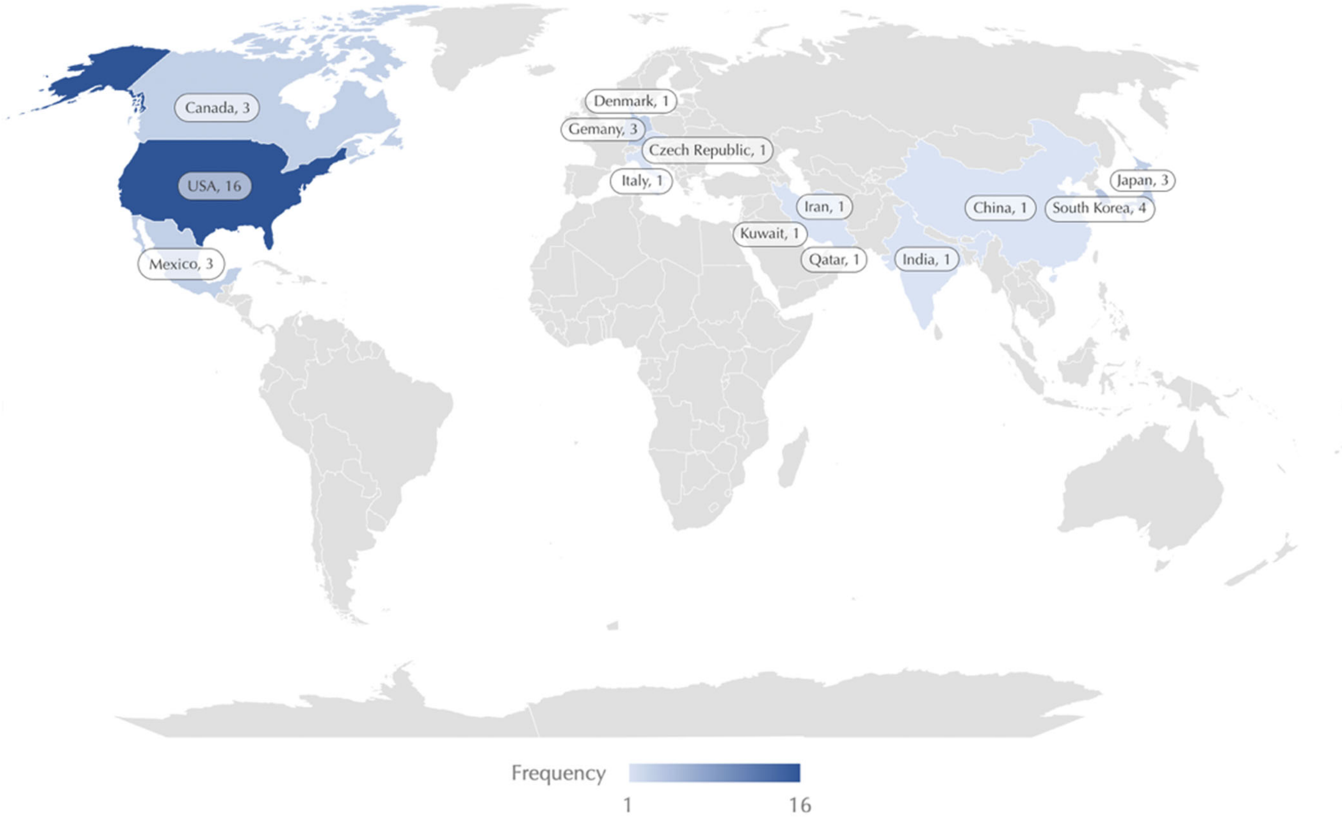

FIGURE 5 | Country scientific production.

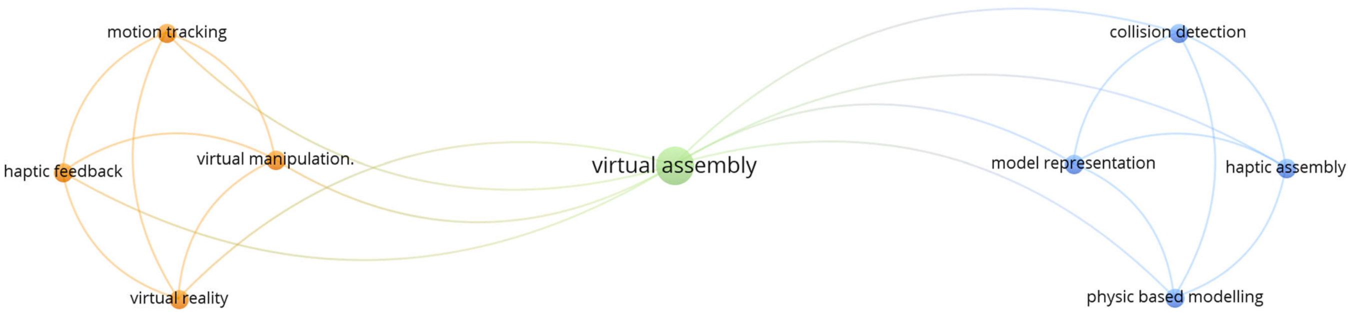

FIGURE 6 | The co-occurrence network of the keywords in 40 selected papers.

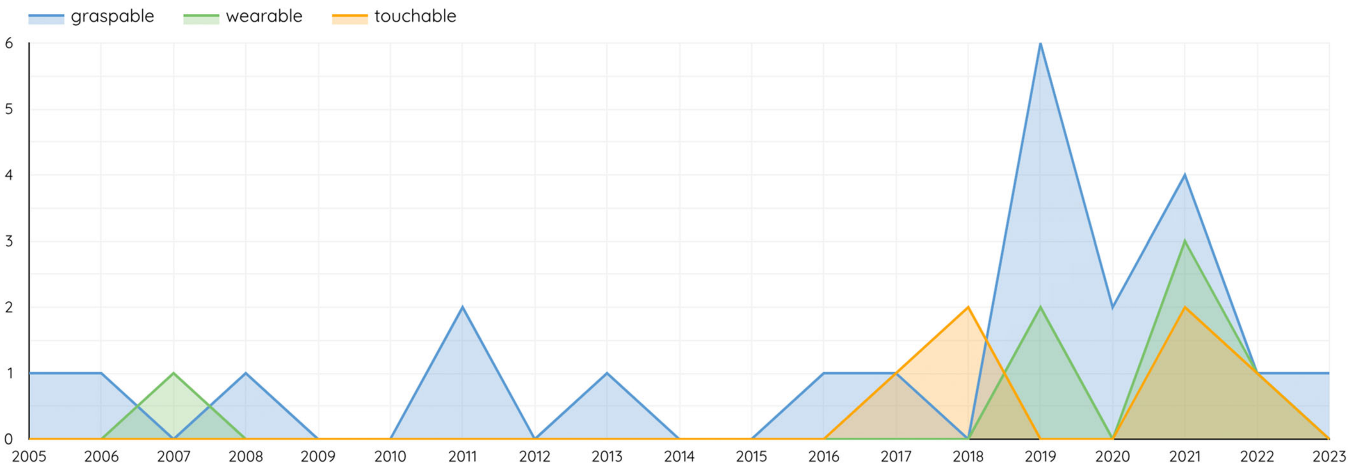

FIGURE 7 | The evolution of different types of haptic devices in STEM learning.

technologies [42] that led to a variety of types of haptic devices among their main categories.

In the early 2000s, haptic devices were focused on providing touch-based feedback using simple vibration motors [43]. Within the analyzed timeframe, the most popular graspable devices, such as Phantom Omni [44], Falcon Novint [45], and Hapkit [19], were constantly used in engineering research. From 2015, graspable and touchable haptic gadgets expanded their capabilities and adopted more advanced feedback mechanisms. As a result, scientists started using upgraded versions of the standard haptic devices and designing custom devices that generate specific feedback to imitate textures [18] and forces [46, 47]. Surface haptic technology has become popular in touchable devices, providing tactile feedback on flat surfaces through vibrations, electrostatic forces, or other methods to simulate textures and sensations [48]. Similarly, it was followed by further developments of wearable haptic gizmos, such as haptic gloves and exoskeletons, which offered a realistic touch experience through a combination of force, vibrotactile, and electro-tactile feedback [49]. In recent years (2021–2023), the focus of haptic device development has been on enhancing VR experiences, along with the creation of devices like haptic controllers, vests, bodysuits, and wearable robotics that can provide multimodal sensing capabilities for mechanical, thermal, and chemical stimuli [50].

3.3 | Synthesis

The next step in the framework presents the results from the appraisals. The outcome is formulated in an organized representation with a hierarchical and relational structure for a clear and systematic approach to representing concepts and facilitating communication. The representation is presented as an H-HTI taxonomy focusing on haptic interventions in engineering learning (see Figure 8).

The taxonomy organizes haptic into categories, each describing the interaction modalities, methods, and technologies focusing on engineering learning. For example, by extracting information on the common elements from a cluster of topics (see Table A1 in the appendix), the haptic HTI was conceptualized into three key components:

- *Human*, in reference to the neurophysiological and biomechanical processes involved in receiving and understanding information through touch;
- *Technology*, in reference to the artifacts and their functions between users and the physical and digital environments;
- *Interaction*, in reference to attributes of feedback and associated parameters.

The conceptualization for the H-HTI taxonomy was guided by existing works that aimed to classify haptic technologies. For example, the authors incorporated the classifications proposed by Kern et al. [33] and Adilkhanov et al. [35] for the technology component. To categorize the human component, we rely on the theories of human perception developed by Grunwald [51] and Fulkerson [52]. The outcomes of the literature review (Table A1) and analysis of the state-of-the-art methods of haptic interaction allowed us to define the elements of the interaction component.

The H-HTI taxonomy categorizes and elucidates the diverse modalities, technologies, and devices employed in HCI within engineering learning. The primary emphasis is on human tactile learning, supported by haptic technology and ultimately applied to engineering processes. The classification aims to highlight specific sensory stimuli vital to a particular application rather than presenting the entire array of stimuli involved in the sensing process. In other words, the taxonomy targets sensory inputs required for a specific task and eliminates nonessential or irrelevant stimuli that might confuse when interpreting haptics tasks and HTI.

The H-HTI in haptic learning taxonomy comprises three major components—human, technology, and interaction—subdivided into subcomponents. To gain a complete understanding of the taxonomy conceptualization, it is necessary to investigate each subcomponent thoroughly. Following are the rationale of each subcomponent and its associated definitions.

3.3.1 | Human

The human component encompasses mechanisms involved in receiving and interpreting tactile cues. The hierarchical arrangement enables a structured comprehension of how the human sensory system perceives and processes tactile information, ultimately leading to certain learning types. The integration of sensory information enables individuals to gain awareness about the different interactions they encounter through touch. Individuals enhance their cognitive abilities and foster a deeper understanding of the relationship between physical stimuli and cognitive processes through tactile experiences. Learning comprises the higher-level cognitive processes that involve haptic experiences in problem-solving, abstract reasoning, and creative thinking. The H-HTI taxonomy provides valuable insights into the nature of haptic interaction from the human perspective. Each H-HTI category under the human component provides an analytical view of the foundations of haptic interaction feedback mechanisms.

The first concept in the human component is *haptic learning*. It refers to acquiring knowledge through tactile experiences and physical exploration [32] (i.e., based on human haptic interaction). According to the clustering of the papers (Table A1) and applications of the haptic systems [33], four types of learning can be defined:

- *Palpability*: It is based on manipulating objects to determine their temperature, texture, shape, and size through the sense of touch [53];
- *Kinesthetics*: It is focused on physical movement and interaction with objects to understand their physical properties by applying forces;
- *Fine motor skills (dexterity)*: It involves precisely controlling small muscle movements, typically in the hands and fingers, to manipulate tools and materials with accuracy and precision;

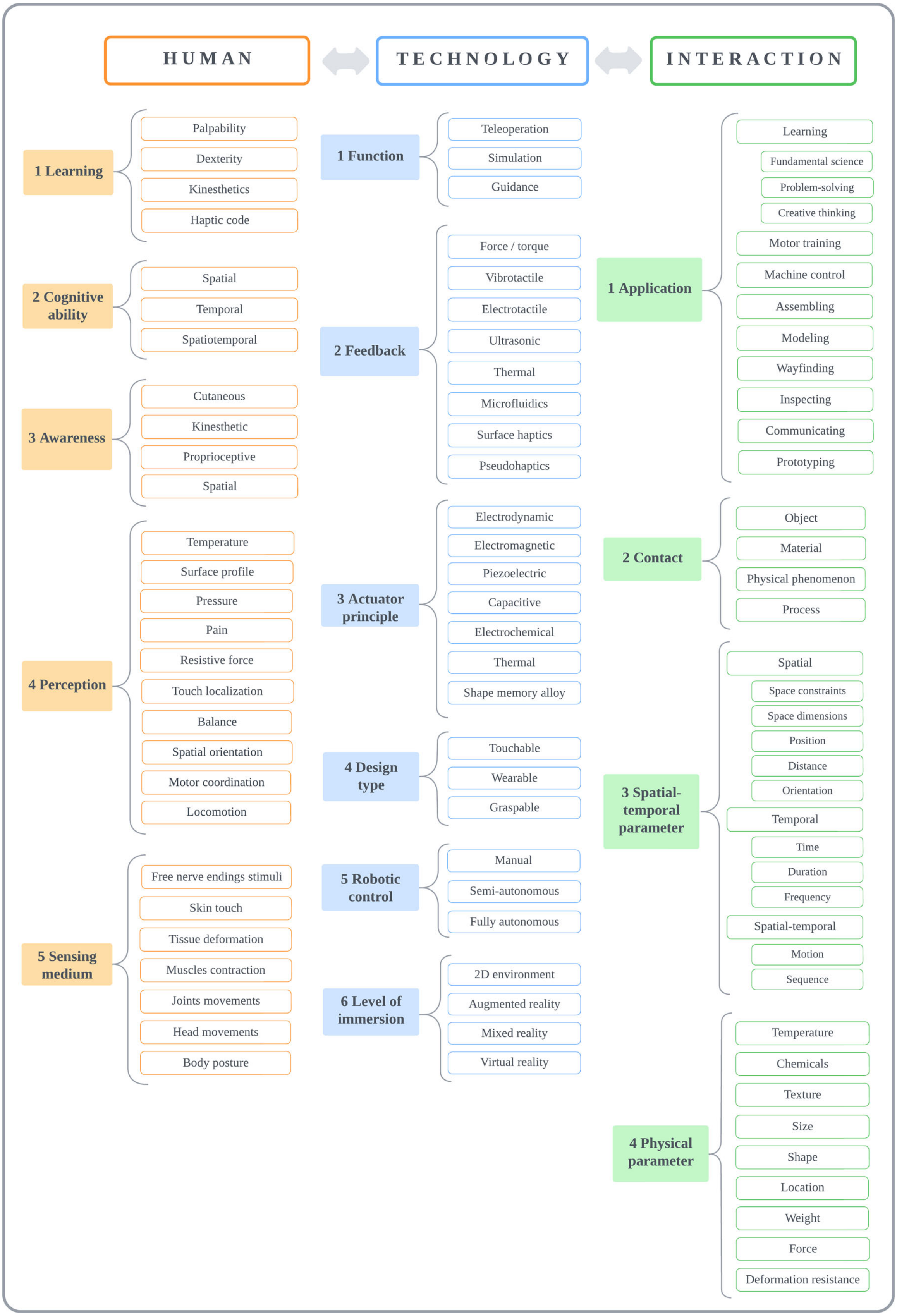

FIGURE 8 | The taxonomy of the haptic HTI in engineering learning.

- *Haptic code*: It is defined by sensory registration of touch-based symbols (akin to a form of haptic icons) that enable communicating information to the user via vibrations, pressure, or movement [33].

The cognitive ability conceptualization in H-HTI taxonomy is herein featured using a framework for processing information in engineering learning named *spatial-temporal cognitive ability (STCA)* [27]. STCA offers the notion that learners effectively manage and comprehend significant amounts of spatial (how to design components are related to one another in the 3D space) and temporal (the logic in a process, such as the order, sequences, and hierarchies of the used components within a problem-solving task) information [27]. Limited or no ability to process spatial and temporal information (i.e., lack of spatial and temporal cognitive ability hinders the understanding of designs and management of the varying local conditions (e.g., unplanned conditions) [27, 54]. The ability helps learners to conceptualize three-dimensional relationships between objects in space and mentally manipulate them as sequential transformations over time.

Learning through haptics—drawing from STCA—allows the learners to recognize meanings and facilitates coupling observed representation to the given contexts. Haptics is a new representational competency. The coupling abilities (spatial and temporal) significantly benefit the decision-making process. Individual spatial-temporal abilities are associated with high cognitive reasoning that defines the cognitive-processing chain—from basic visual attention to higher-level reasoning, such as an interaction between organizing, performing, and supervising the effectiveness of a plan [27]. For instance, planning is a highly cognitively demanding task where STCA plays a pivotal role. Planning is critical as the learner couples observed representation in a given context to organize, perform, and supervise the effectiveness of a plan while interpreting information from engineering designs. Using STCA, haptic learning enables individuals to instantly identify concepts, events, and patterns for comprehension and projection, streamlining actions, solutions, and implementations in planning.

Learning by involving haptics is characterized by *haptics awareness*, which refers to the knowledge and conscious experience of touch-based information received by the human sensory systems [55].

Drawing from the examination of multisensory aspects of perception by Fulkerson [52], encompassing the multisensory aspects of perception, the correlation between perception and action, and the interrelationship between touch and bodily awareness, four types of awareness can be distinguished:

- *Cutaneous*, with four submodality focus: tactile (pressure, temperature, texture, and vibration), thermal, painful (chemical and electric stimulation), and pruritic (itch);
- *Kinesthetic*, the sensation of the position and movement of one's body parts;
- *Proprioceptive*, the perception of space, including position and orientation of the body, to coordinate movements and maintain balance, and
- *Spatial*, the perception of one's position in relation to objects in a given space, helping to navigate through space, estimate distances and sizes of objects, and understand how objects relate to one another in space.

Kinesthetic and proprioceptive awareness focus more on the body's internal sensations, whereas spatial awareness focuses on the external environment and how the body interacts [52].

Cognitively processing haptic awareness can be divided into three stages: recognition, perception, and reception.

Recognition is the ability to identify and categorize objects depending on their tactile properties (shape, size, texture) to create a cognitive representation of them [56]. When recognizing objects, humans consider their spatial-temporal and physical parameters [57], which are listed as the elements of the interaction component (Figure 8).

Perception is "the process of acquiring, interpreting, selecting, and organizing sensory information" ([51], p. 653). It involves integrating sensory information with prior knowledge and experience to form conscious experience. The perceived cutaneous sensations are decoded as information about the external temperature, presence of vibration, pressure, pain, resistive force, surface relief of objects, and their localization in relation to the body [58]. Kinesthetic sensations include fine motor skills and locomotion. Proprioception denotes the complex integration of signals originating from muscles, skin, joints, and the central nervous system, indicating the sensory perception and awareness of the body's position, movement, and actions [59].

Perception is the outcome of processing the following information, drawing from Grunwald [51]:

- *Temperature* (the variations in warmth or cold through direct skin contact with an object's surface or in proximity to the object ([51], p. 103));
- *Surface profile* (defined as the physical characteristics of a surface, such as variations in roughness, contours, and texture patterns [60]);
- *Pressure* (the maintained distortion of the skin, such as an indentation, that increases linearly ([61], pp. 87–116));
- *Pain* (represented as unpleasant sensations caused by extreme mechanical, thermal, or chemical stimuli that may be harmful or damaging to the body [62]);
- *Resistive force* (the force that opposes a body's motion and acts in the opposite direction of the body's velocity [63];
- *Touch localization* (the process of mentally mapping the area of the body, i.e., the recipient of mechanical stimulation [64]);
- *Balance* (the ability to effectively maintain the alignment of the body's center of mass with the vertical line of gravity while minimizing postural sway [65]);
- *Spatial orientation* (the mental mapping of the position, orientation, and movement of the body within the surrounding environment to navigate in space [66]);

- *Motor coordination* (the synchronized and purposeful interaction between two or more effectors, such as muscles, joints, limbs, or even individuals, to accomplish a specific behavioral task [64]), and
- *Locomotion* (the directional movement or the ability to move from one place to another, e.g., walking, running, swimming [67]).

Haptic reception is a mechanism of the sensory information processing from touch-based stimuli through the *sensing medium*—the somatosensory system detecting pain, temperature, head and body position, head and body movement, and touch [68]. Cutaneous receptors provide sensing of skin touch, pressure, texture, and heating or cooling of tissues [69]. Some tactile sensations can be perceived without physical contact or proximity to the source of stimulation, such as the air pressure of ultrasound and the flow of wind. Extreme touch sensations, such as high and low temperatures, pressure, and chemical and electrical stimulations, are perceived as pain by activating nociceptors in the skin [58]. Musculoskeletal receptors detect the motor activity in the muscles and joints of the body that can be sensed as muscular effort, muscle contraction, and movements of body parts [70]. Considering the foundational theories in neurophysiology [51, 59], haptic reception is mediated by the following mechanisms:

- *Free nerve endings stimuli* distinguish pain, hot and cold, and light touch ([51], p. 91);
- *Skin touch* activates skin mechanoreceptors that respond to touch, skin displacement, stimulation of skin derivatives (such as hairs), and fluid movements or vibrations elicited by physical contact with the skin ([51], p. 89);
- *Tissue deformation* means the mechanical alteration of body tissues caused by external forces such as pressure ([51], p. 86);
- *Muscle contraction* is the process of shortening or tightening muscles to generate force to perform biomechanical work ([51], p. 87);
- *Joint movements* refer to the perception of joint position and motion relative to one another ([51], p. 102);
- *Head movements* involve the processing of sensory information regarding the body's position, direction, and movement, which is carried out by the vestibular system located in the head [59];
- *Body posture* is the position and alignment of body parts in relation to each other and the environment [59].

3.3.2 | Haptic Technology

Haptic technology is a component representing mediation between the learners and the environment. Through haptic interfaces, users can experience tactile sensations, enabling them to feel and manipulate objects, textures, and forces for actions in the virtual and physical environment or any combination of physical and virtual environments. The component encompasses various subcomponents in the taxonomy. The subcomponents work together to define the features of the employed haptic device, ensuring that the device actions align with a specific learning task and the related characteristics of the environment.

Haptic technology is characterized by its *functions*, including teleoperation, simulation, and guidance according to the main application domains Adilkhanov et al. [35]. Definitions follow.

- *Teleoperation* is the remote control of a robotic system using a haptic interface operated by a human. The haptic interface provides a bidirectional communication channel between the operator and the remote environment, allowing the operator to perceive tactile feedback from the robotic tool [71]. It enables the operator to intuitively and precisely control the robotic tool, replicating their sense of touch and allowing them to perform tasks remotely while experiencing haptic sensations that correspond to the interactions of the tool with the environment. Examples include generating sensations on the user's fingertips to improve grip force control and directional information through vibration about collisions perceived by the controlled robot [72].
- *Simulation* implements haptic feedback to imitate physical interaction with the environment to increase the realism of learning scenarios [73]. For instance, haptics-based simulators can be used to imitate working conditions to raise awareness of safety requirements for construction workers.
- *Guidance* employs haptic feedback to represent patterns for specific actions or messages independently of auditory and visual channels [74]. For example, vibrotactile feedback is often incorporated into commercial smartwatches to guide and alert users via haptic notifications.

Technology mediators comprise human touch sensations for their operations through communication and feedback. Conveying information to the user is known as haptic feedback. Modern haptic devices produce several types of *haptic feedback*, as outlined by Kern et al. [33], considering the latest advancements in haptic technology [75]:

- *Force feedback* is an exerted force on the user's hands, limbs, or whole body generated by a mechanical device. This feedback type is commonly incorporated into graspable devices and modern haptic gloves.
- *Vibrotactile feedback* is the stimulation of human skin receptors evoked by mechanical vibrations. For instance, joysticks, VR controllers, and steering wheels have embedded vibrotactile feedback.
- *Electrotactile feedback* is a sensation that imitates the texture of objects through haptic gloves, vests, and suits. It is possible to obtain different types of sensations depending not only on the intensity and frequency of the signals delivered to the skin but also on the voltage, material, waveform, electrode size, contact force, and hydration.
- *Ultrasonic mid-air haptics* is a force that can be felt on the user's hand by the combined pressure of the waves manipulating ultrasound waves. Akin to a "virtual touch," haptic technology eliminates the need for the user to touch a physical surface to feel the effect.

- *Thermal feedback* utilizes the haptic actuator's grid, composed of thermoelectric diodes, to generate heating or cooling effects.
- *Microfluidics* involves the creation of localized pressure or temperature pockets on the user's skin through the utilization of small chambers within the device (for instance, innovative haptic gloves), typically constructed using flexible silicone panels.
- *Surface haptics* is tactile by modulating friction between a finger and a touchscreen.
- *Pseudo-haptic feedback* is distorted and overcome by other modalities of haptic perception. It does not absolutely depend on the physical actuators [76].

Actuators are essential components of any haptic device that generate haptic sensations. Their selection and design determine the entire quality of the haptic impression. Haptic actuators differ in terms of their physical operating concept that defines how to transform an arbitrary energy source into mechanical energy. Kern et al. ([33] pp. 310–312) developed a classification of haptic actuators based on the working principles:

- *Electrodynamic* utilizes the force acting upon a current-carrying conductor, known as Lorentz's force;
- *Electromagnetic* employs the force acting upon the magnetic circuit based on the enclosed energy;
- *Piezoelectric* implements the force induced in crystals by applying voltage;
- *Capacitive* involves the force generated when charges attempt to minimize the energy stored in a capacitor;
- *Electrochemical* refers to displacement or pressure within a closed system where a substance emits a gas;
- *Thermal* pertains to changes in the material's length when it is cooled or heated based on the material's coefficient of thermal expansion; and
- *Shape-memory alloys* shift from one crystal structure to another when exposed to relatively small temperature changes [77];

The most used actuators for haptic devices are eccentric rotating mass actuators, linear resonant actuators, and piezoelectric actuators [33, 78].

According to the wearability-based taxonomy [35] concerning the *design types*, haptic devices fall into three categories of haptic systems:

- *Graspable*, containing holdable tools that can be pushed (and pushed back) by using kinesthetics. The most popular examples of graspable gadgets are joysticks, steering wheels, and widely used devices for education and research, such as "Phantom" and "Omega."
- *Wearable*, delivering sensations (vibration, skin stretching, and normal skin deformation) directly to the skin through tactile (cutaneous) devices mounted on the hands or other parts of the body. There is a wide variety of wearable haptic gadgets, such as watches, gloves, vests, and suits [79].
- *Touchable*, enabling tactile interaction with virtual objects through pure cutaneous feedback using vibrotactile, electrostatic, or ultrasonic actuation. For example, TeslaTouch [80] is a touchscreen device that employs cutaneous feedback through electrovibration.

Robotic control refers to the methods that control the actions and behavior of robots through haptic technology. Following the comprehensive framework presented by [51], haptic control can be classified into three types: manual, autonomous, and semiautonomous robotic.

- *Manual* is when a human operator directly controls the robot's movements and actions through a control interface, such as a joystick or keyboard. It is often applied when precision and fine control are required, such as in surgery or hazardous environments.
- *Autonomous* is implemented for cases when the robot makes decisions and controls its own actions without direct human intervention. This type is commonly used in applications where the robot must operate independently, such as in space exploration or autonomous vehicles. Autonomous control often involves the use of algorithms, sensors, and machine learning techniques to enable the robot to make decisions and control its own actions.
- *Semiautonomous robotics implies* that robot operations are partially under human and partially under autonomous control. In this case, the robot performs certain actions and decisions independently, but the human operator can intervene and control the robot's actions in real-time, as needed. It is used in applications where a robot operates in complex and unpredictable environments or where it is necessary to balance the benefits of autonomous operation with the need for human supervision and decision-making.

Level of immersion: Haptic feedback is applied to complement the immersion and interaction with the different types of the digital environment [81], such as:

- *Virtual reality* (*VR*), presenting a completely artificial digital environment designed to simulate a physical environment or create an entirely new world. It is typically experienced through a VR headset that completely covers the user's eyes, providing a fully immersive experience.
- *Augmented reality* (*AR*), overlaying digital information or objects onto the real world, enhancing or adding to the user's perception of the real environment. AR can be utilized through a smartphone, tablet, or head-mounted display.
- *Mixed reality* (*MR*), combining elements of both VR and AR, eventually creating a digital environment that seamlessly integrates virtual and real-world elements. In MR, digital objects can interact with the real world and vice versa, creating even more interactive experiences.

3.3.3 | Interaction

The interaction component presents a set of attributes and their associated parameters that address engineering problems by integrating haptic feedback. The study explores relevant applications and learning scenarios incorporating interaction attributes, including objects, materials, physical phenomena, and processes. Accordingly, each type of interaction within digital space is characterized by its spatial-temporal and physical parameters, which are replicated by haptic technology.

By combining the data from the relevant papers (Table A1) and outcomes of the review of multimodal HTI *applications* [31], haptics can be applied as an assistance tool in engineering for various purposes, such as:

- *Learning* incorporating haptic technologies into educational tools and simulations to facilitate the knowledge outcomes [82]:

  - *Fundamental science* knowledge by simulating, conducting scientific experiments, or exploring complex systems. For instance, haptic interfaces were applied to teach students the structure and properties of different materials, enabling them to develop embedded learning of scientific concepts [83].
  - *Problem-solving* skills by enabling the ability to conduct precise analysis and evaluation, derive effective solutions for complex situations, and adapt the approach through real-time feedback for continual refinement. For example, advanced problem-solving skills aim to improve the perception of reality and efficiently navigate the complexities of construction-related tasks [54].
  - *Creative thinking* skills by offering students new ways to interact with digital models and explore scientific concepts. New techniques for creating and manipulating objects can be developed by incorporating haptic technologies into art and design programs, eventually leading to new forms of artistic expression and innovation [84]. It can be especially beneficial in engineering and research, where students must design models and test prototypes.

- *Motor training* offers instantaneous feedback on movements, enabling users to enhance their coordination and control of their body parts [85]. It will help to reduce the risk of injury or damage to equipment by allowing trainees to practice in a safe and controlled environment. In construction engineering, for instance, a haptic simulator can be implemented to train crane operators, allowing them to practice operating the equipment in various scenarios and to receive haptic feedback when they make mistakes [86]. Similarly, haptic simulators can be used to train workers in operating power tools, handling materials, and performing other tasks safely and efficiently [87].

- *Machine control* by allowing machines and robots to be remotely controlled in hazardous or inaccessible environments. Through haptic feedback, the operator can sense the forces and vibrations experienced by the machine or robot, allowing them to make more precise and accurate movements [26].

- *Assembling* by guiding operators in assembly and manufacturing tasks, such as aligning parts or tightening screws. In such cases, the users can feel the correct position or amount of force required, which can help reduce errors and improve quality [88].

- *Modeling* by involving haptic gadgets in the design process and enabling physical interaction with digital models. Employing haptic feedback, designers can sense the shape and texture of virtual objects, facilitating a quicker and more efficient refinement process that ultimately results in improved designs [84, 89].
- *Wayfinding* by enabling navigating through environments in conjunction with digital maps, providing users with directional cues [90]. For example, haptic feedback can signal when a worker approaches a dangerous area that will help workers navigate safely through the site [91].

- *Inspecting* by helping workers to identify defects or anomalies in materials or structures and enabling instant monitoring of the condition of buildings for maintenance and inspection purposes [92].

- *Communication* by facilitating information exchange in construction settings, particularly in noisy environments or in situations when verbal communication is impossible [93]. For example, haptic devices can indicate the location of underground pipes or wiring, making it easier for workers to avoid damaging them during construction. Haptic interfaces can provide actual information to workers on site about the status of the construction project and changes in design or schedule. Consequently, it will improve communication and reduce errors and delays [94, 95].

- *Prototyping* by customizing haptic devices to develop precise and tailored haptic feedback experiences. Developers can experiment with different haptic sensations, intensities, patterns, and frequencies through customization to find the most optimal feedback for a particular use case. It allows for rapid iteration, user feedback integration, and the exploration of new possibilities in various fields [96]. For example, the Phantom is the most frequently used haptic device in research, allowing users to feel virtual objects and surfaces through a variety of forces and sensations [44]. In addition, wearable devices designed for movement-based interactions and force-feedback joysticks used for control-based interactions, such as controlling a robotic arm or steering a virtual vehicle, can provide customized haptic feedback [97].

Contact: Haptic technology enables a tactile way of interacting with the digital environment via contacting virtual objects, different materials, physical phenomena, and imitating the performance of various engineering processes. Considering the variety of modern haptic interfaces [35], the H-HTI taxonomy categorizes haptic interactions into the following types:

- *Object*, by manipulating virtual objects and determining the object's size, shape, weight, and other mechanical properties through their resistance to deformations;

- *Material*, by replicating surface characteristics, such as roughness, smoothness, or texture patterns;

- *Physical phenomenon*, by creating variations in temperature and pressure

- *Process*, by imitating different activities such as virtual manufacturing, training, gaming, social interactions, etc.

Spatial-temporal parameters refer to the attributes of movement that describe how objects move through space and time [98], and the following groups apply:

- *Spatial parameters*, defining the characteristics of the digital environment, such as *space constraints* (the volume of the space), *space dimensions* (the size of the space), one's *position* and *orientation* in the given space, and the *distance* to other objects. Basically, spatial parameters are represented through vibrotactile feedback to convey information about the properties of the space in a virtual environment [99];
- *Temporal parameters*, comprising *time*, *duration*, and *frequency* of events that can be sensed through changes in the intensity, sharpness, and duration of vibrations or forces;
- *Spatial-temporal parameters*, including complex subcomponents such as motion and sequence. A *sequence* is a set of related components, movements, or events organized in a particular order [100]. In engineering, sequences refer to the specific series of steps and processes followed in engineering projects to attain required outcomes (e.g., a manufacturing process and construction project scheduling). *Motion* is characterized by distance (the length of the path), time (duration of movement), speed (the distance traveled per unit of time), displacement (change in position), velocity (rate of displacement change), and acceleration (rate of velocity change) [101]. Virtual motion simulations can be represented through activities like exploring a construction site, assembling a building, and operating equipment.

The outcomes of the literature review (Table A1) and contemporary methods of haptic interaction [102] indicate that haptics can imitate a wide range of *physical parameters* of the objects, including:

- *Temperature*: To simulate heat or cold, thermoelectric modules can transform electrical energy into thermal energy and vice versa [103];
- *Chemicals*: Some liquid stimulants can render unpleasant (e.g., tingling, numbing, stinging) or even painful sensations caused by chemical reactions with the skin [104];
- *Texture*: Small vibrating motors can create different types of surfaces, imitating their roughness or smoothness through friction [18, 105];
- *Size, shape, location, and weight of objects*: Haptic gadgets that utilize force feedback, such as haptic gloves, can replicate the tactile and kinesthetic sensations of holding and manipulating objects and emulate their geometry [29, 106];
- *Force and deformation resistance*: Using force feedback mechanisms, haptic technology reproduces the resistance and pressure of physical objects and mimics their physical properties, such as hardness, stiffness, and elasticity [107].

3.4 | Analysis

This last framework step maps the frequency of selected papers' topics (organized by clusters) and the H-HTI taxonomical concepts. The results are presented using heatmaps (see Figure 9a–c) to visually represent the frequency of intersections between taxonomy components and HTI topics. The heatmaps allow the identification of the most prevalent factors that impact haptic HTI.

The *human* aspect of learning heavily relies on *kinesthetic, tactile, and dexterous* experiences. Within this context, key components involve *skin touch, muscle contraction, and joint movements* reflecting *touch localization, resistance forces*, and *locomotion* that consequently develop *kinesthetic and spatial awareness*.

On the *technology* front, the implementation often revolves around *2D* and *VR simulations* of engineering tasks. These simulations employ *graspable devices* equipped with *electromagnetic actuators* to provide *force* or *vibrotactile feedback*.

The *interaction* component finds its primary applications in *learning fundamental science* concepts and *prototyping* customized haptic experiences that enable manipulations with various *objects* in diverse engineering *processes*. These interactions encompass a wide range of haptic parameters, covering *space dimensions and constraints, position, distance, orientation, time, duration, motion*, and *sequence*. Among the frequently considered physical parameters are the *size, shape*, and *location* of the objects, as well as *force* and *deformation resistance*.

The further descriptions involve the following abbreviations for the taxonomy clusters (see Figure 8), where three major components—human (H), technology (T), and interaction (I)—are split into subcomponents numbered from top to bottom. For instance, "T-4" means that the element belongs to the category "4 Design type" of the "Technology" component.

The examination of the intersections among *human*, *technology*, and *interaction* components (see Figure 9a–c) reveals their interdependencies. For example, primal research experiments utilize graspable haptic devices (*T-4*), such as Phantom Omni and Novint Falcon with force and torque feedback, to facilitate comprehension of fundamental science concepts—a cognitive dimension—(*H-2*), typically kinesthetic forces (*I-4*). As altered realities were not widely used at that time, most experiments were conducted utilizing 2D screens (*T-6*).

Later, the emphasis shifted toward implementing advanced tools and systems, including virtual and augmented environments *(T-6)* complimented by sophisticated haptic devices. Figure 9a shows the following prevalent trend in adopting VR simulations (*T-1*) to straighten problem-solving skills (*I-1*) by exercising individual spatial-temporal cognitive abilities (*H-2*) (according to Figure 9b). Teleoperation (*T-1*) comes into play to control engineering systems remotely and perform assembly tasks (*I-1*) by dexterous and kinesthetic movements (*H-1*). Other strategies, such as guiding algorithms with VR and AR (*T-6*), aim to tackle engineering problems more efficiently, control machines, assemble parts, and navigate the environment (*I-1*), relying on spatial and kinesthetic awareness (*H-3*). While predominantly based on manual guidance, there is an apparent shift toward incorporating semiautonomous and fully autonomous robotic control (*T-5*).

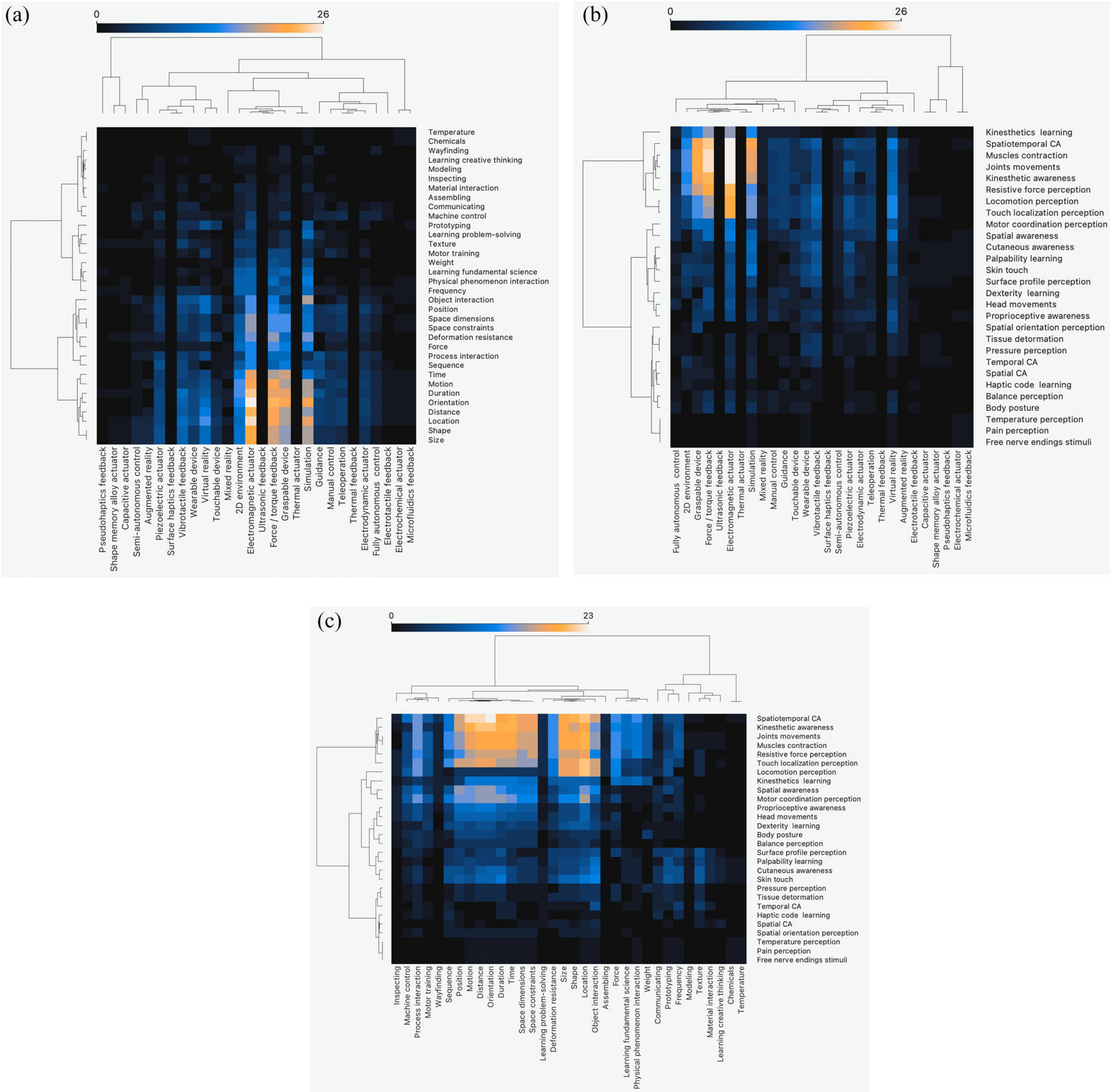

FIGURE 9 | The frequency of intersections for each pair of the taxonomy components: (a) Technology-Interaction, (b) technology-human, and (c) interaction-human.

In recent years, a growing trend has been toward wearable haptics (T-4), such as gloves and vests, increasingly finding utility to address particular engineering challenges. Modern haptic interfaces with adapted feedback (*T-2*) are designed to target certain tactile senses, providing cutaneous sensations (*H-5*), for example, by applying thermal and chemical feedback *(T-2)*. As technology advances, we can anticipate a broader range of haptic gadgets offering intricate and compound feedback to resolve specific engineering tasks by applying creative thinking and problem-solving skills (*I-1*).

When designing haptic devices (T-3), the most commonly used actuators are those based on electromagnetic, electrodynamic, and piezoelectric principles (Figure 9a,b). Conventional haptic controllers have relied on electromagnetic actuators, which offer substantial vibration displacement but have limited versatility in vibration frequencies. Consequently, their applications have primarily centered around basic vibration notifications. Alternatively, piezoelectric actuators are well-suited for surfaces requiring high-frequency tactile feedback, offering swift and precise responses. Emerging technologies like tactile displays, proving noncontact tactile stimulation, and skin integration as haptic interfaces are expected to expand the range of application frequencies and sensitivity of tactile perception (*H-4*).

Generally, the haptic features of graspable and wearable devices (*T-4*) allow interaction with almost all sets of spatiotemporal (*I-3*), mechanical, and kinesthetic parameters of objects (*I-4*) (see Figure 9a). From the human side (see Figure 9c), it involves palpable exploration and kinesthetic movements along with fine motor skills (*H-1*), which in combination develop kinesthetic and spatial awareness (*H-3*) that subsequently foster spatiotemporal cognitive abilities (*H-2*).

Figure 9b reveals that a promising avenue lies in acquiring haptic code (*H-1*) using wearable devices with vibrotactile feedback (*T-2*) implicating distinct haptic patterns. This method can be implemented in virtual and mixed-reality simulations (*T-6*), augmenting guidance (*T-1*), and enhancing the interaction between the user and the haptic interface. As Figure 9c demonstrates, this approach can significantly enrich learners' spatial and temporal cognitive abilities (*H-2*) by enabling a more intuitive engagement with intricate spatiotemporal features of objects (*I-3*), such as sequences and hierarchies.

Finally, Figure 9c illustrates an evolution of the interaction level between human and technology in terms of contact (*I-2*)—from manipulating simple objects and imitating their parameters to modeling complex situations with a whole range of attributes, producing a holistic haptic experience (*T-2*). This extension of environmental attributes engages a broad spectrum of sensory modalities (*H-4*) in the interaction process that contribute to a compound learning profile encompassing an array of performance metrics.

4 | Taxonomy Use Example

The main purpose of the H-HTI framework (Figure 8) is to simplify and facilitate the creation of an immersive learning environment that implements the maximum potential of extended realities with a focus on haptic technology considering human learning capabilities. The framework addresses the following key questions when designing a learning scenario:

- What type of learning should be implemented?
- What cognitive and physical skills are developed through this HTI?
- Which human sensory channels are involved in the particular interaction?
- What is the main function of haptic technology to provide the most effective learning experience in each instance?
- What additional attributes should be incorporated for a holistic structure?
- What interactive features are present in the learning environment?
- How are attributes of human, technology, and interaction related to each other?
- What other application can be implemented to enhance the learning scenario?
- How do we maximize the learning outcomes through the immersive experience?

The following guide presents a step-by-step process for setting up a learning environment using an immersive VR platform enhanced by haptic technology. The flow of taxonomy use is demonstrated in Figure 10.

Step 1: Identify key learning objectives and competencies

Begin by indicating the primary learning objectives and competencies required for the engineering domain; they will serve as a basis for selecting the attributes of each taxonomy component. Target competencies may encompass cognitive skills (e.g., spatial reasoning, problem-solving) and practical skills (e.g., manual dexterity, precision).

Step 2: Map tasks to haptic technology capabilities and select the devices

Align specific tasks and competencies with the capabilities of haptic technology to enhance the learning experience through HTI. Select the XR and haptic devices, noting their technical specifications, which afterward will dictate the technology attributes. Create a list of initial attributes according to the learning objectives.

Step 3: Build relationships between the attributes

Using the taxonomy, determine the other subcomponents involved in the interactive process. To ensure the accuracy of these choices, referencing the H-HTI taxonomy's descriptions of each attribute is recommended. Through reasoning, define the relationships between attributes, that is, connect the attributes from different components, ensuring the logical flow of HTI. Put the major focus on the first row of the taxonomy by determining the human learning type, haptic technology function, and application to the context.

Step 4: Derive learning scenarios

Based on the defined relationships of the H-HTI attributes, develop detailed interaction scenarios incorporating haptic

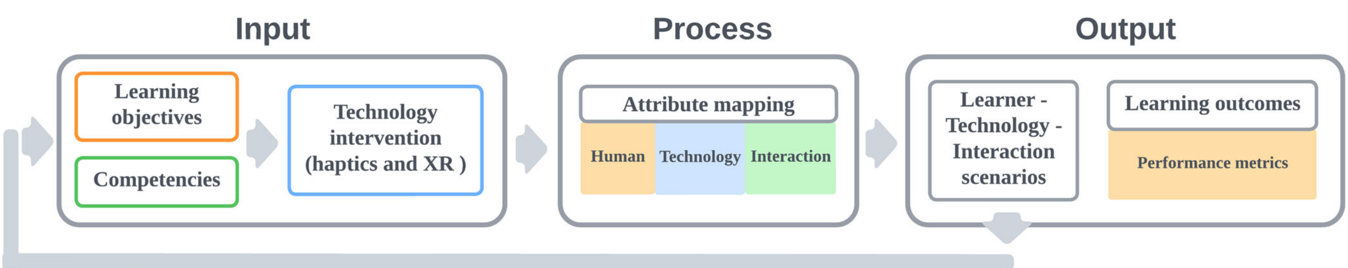

FIGURE 10 | The flow of taxonomy use.

technology to support learning tasks. The learning scenario is generated based on the conceptualization of the relationships between taxonomy attributes through reasoning to meet the objective. Describe the flow of HTI for the chosen context.

Step 5: Revise the objectives and refine the outcomes

Ensure the developed output aligns with the initial learning objectives and competencies established in Step 1. Reassess the learning scenario using the taxonomy to identify areas for further improvement, incorporating additional features that could enrich the immersive learning experience. Revisiting the flow and components will help maximize the potential of the human, technology, and interaction components, ensuring that the final learning scenario is highly effective in achieving the anticipated learning outcomes.

Step 6: Evaluate learning outcomes

Define the human performance metrics to assess the effectiveness of haptic technology in benefiting learning outcomes through qualitative and quantitative measures. The data on user performance, engagement, and feedback will help validate the impact of the haptic-enhanced learning environment.

4.1 | Example of the Taxonomy Use for a Learning Scenario in Construction Engineering and Management

To demonstrate the practical implementation of the H-HTI framework, the taxonomy was applied to design a learning scenario for a construction planning task within the Construction Engineering and Management discipline.

The study objective is to explore human-machine interactions to determine a more efficient way for CEM students to enhance perception and reasoning skills that will help them interpret the information in design documents, drawings, and specifications.

The learning environment will incorporate visual and haptic interactions within an immersive VR platform, allowing CEM learners to interact with virtual representations of building components (walls, columns, windows, etc.) for a planning task. Haptic feedback will be used to feel the physical manipulations with building components and to imitate their semantics regarding the work breakdown structure (WBS).

Input information for this study objective is presented in Table 1.

TABLE 1 | Input for the learning scenario in CEM.

Human	Technology			Interaction	
Skills	VR environment	XR headset	Haptic devices	Field	Task
Spatial reasoning, Temporal reasoning, Spatial awareness, Abstract reasoning, Numerical reasoning, Visual perception	Construction site with building components (columns, walls, windows, etc.) representing WBS	VR headset (Meta Quest 3)	Haptic gloves (bHaptics TactGlove DK2), a haptic vest (bHaptics TactSuit X40)	Construction engineering and management	Construction planning for assembly of building components

4.1.1 | Attribute Analysis

Each attribute of Interaction, Technology, and Human components is reviewed to determine its presence in the VR environment. The application type defines the contact and interaction parameters. Understanding the haptic devices, their features, and working principles helps determine the haptic functions necessary for the engineering application. Lastly, the human learning type is derived from the haptic function and application. Perception attributes are defined based on the learning type and specifications of the haptic devices. The analysis result is demonstrated in Table 2.

4.1.2 | Learning Scenario Description

The study introduces a technology environment using VR and real-time haptic feedback for assembling tasks in Construction Engineering and Management. By complementing the semantics of visualizations (3D designs) with haptic feedback (vibrations), the approach facilitates a more immersive and effective learning experience. The framework integrates intersecting components, such as the virtual environment, its interactive parameters, haptic (vibrotactile) code, and spatiotemporal cognitive abilities to perform assembly tasks. The technology enables learning through observation and VR-based manipulation of design components, using work packets (construction product deliverables) to simulate real-world planning tasks. These work packets serve as manageable chunks of workload, representing the smallest unit that can be planned and managed in construction operations. By focusing on work packets, the approach helps learners understand planning by framing it as a process of construction assembly. This method allows learners to assimilate complex simulated realities and develop spatial-temporal cognitive abilities, Spatial-temporal ability will allow learners to effectively manage and comprehend significant amounts of spatial (how components are related to one another in the 3D space) and temporal (the logic in a process, such as the order, sequences, and hierarchies of the resources within a construction task) information [108]. The outcome demonstrates that haptic feedback (haptic code) effectively communicates the semantics of components within the planning task, allowing learners to infer conditions in a virtual scene.

4.1.3 | Revision for Improvement

Revising the learning process flow through the H-HTI framework reveals several areas for potential improvement:

- *Enhancing application domains:* The scope of the tasks can be expanded by combining problem-solving skills with assembly tasks, progressing from the assembly of building components to the management of broader construction activities.
- *Incorporating advanced haptic devices*: Introducing more sophisticated haptic devices with complex feedback mechanisms, such as force-feedback haptic gloves, can increase user engagement by involving more senses and enhancing the learning experience.
- *Upgrading to mixed reality:* Transitioning from VR to MR can improve the interaction between real and artificial environments, offering the benefits of both and providing a richer learning experience.

After identifying these potential improvements, researchers can evaluate which are both reasonable and feasible to implement

TABLE 2 | Output for the learning scenario in CEM.

Human		Technology		Interaction	
Learning:	**Haptic code**	**Function:**	**Guidance**	**Application:**	**Assembling**
Cognitive ability:	Spatiotemporal	Feedback:	Vibrotactile	Contact:	Object
Awareness:	Cutaneous, Spatial	Actuator principle:	Electromagnetic	Spatial-temporal parameter:	Space constraint, Space dimensions, Position, Distance, Orientation, Time, Duration, Sequence
Perception:	Pressure, Touch localization, Spatial orientation	Design type:	Wearable	Physical parameter:	Size, Shape, Location
Sensing medium:	Free nerve endings stimuli, Tissue deformation	Robotic control:	Manual		
		Level of immersion:	Virtual reality		

to achieve the learning objectives. If not immediately applicable, these suggestions can serve as directions for future studies.

4.1.4 | Learning Outcomes Assessment

The assessment of the immersive VR platform will evaluate the holistic experience based on user feedback on presence, engagement, immersion, flow, usability, skill, emotion, experience consequence, judgment, and technology adoption. For aspects related to the functionality of haptic cues, users will evaluate the utility of haptic technology and its guiding function (e.g., the accurate perception of haptic patterns to function as an intervention for interpreting designs). Also, the performance metrics, such as task completion duration and error rate, will provide objective insights into the effectiveness of the learning scenario. This study will underscore the significant potential of VR and haptic feedback to enhance the learners' perception of a problem's conditions that are not immediately visible to the learner.

4.2 | Example of the Taxonomy Use for Learning Scenario in OSHA Training (Scenario in Engineering Learning: Occupational, Safety, and Health Administration, OSHA, Training)

An illustration for implementing the taxonomy is a learning scenario for OSHA Training to learn safety standards in the construction sites, using MR and haptic feedback. The objective is to use HTI as a more effective way to train workers and trainees. The focus is on hazard identification, situational awareness, and safety protocols [109]. The expected outcome is to enhance learning outcomes by adding a new modality (haptics) to the visual immersive experience in safety training—combining visual MR experiences with tactile feedback.

The learning environment incorporates MR and haptic interactions to simulate construction site tasks in a workplace environment. Trainees wear MR headsets (e.g., Microsoft HoloLens) to visualize safety hazards, such as exposed wiring, unsafe machinery, or slippery surfaces, and use haptic vests to experience potential hazards physically. The haptic feedback will allow learners to feel elements such as machinery vibrations, providing a realistic and hands-on understanding of OSHA standards.

Input information for this study objective is presented in the Table 3.

4.2.1 | Attribute Analysis

Understanding the MR and haptic devices, their features, and working principles helps determine the functions needed for the safety training application. Each Interaction, Technology, and Human attribute related to haptics is reviewed to determine its presence in the MR environment. The table highlights the taxonomical components of the haptic interaction in the analysis. It is understood that the MR involves a visual-haptic experience. The analysis result is demonstrated in Table 4.

TABLE 3 | Input for the learning scenario in OSHA training.

Human	Technology			Interaction	
Skills	MR environment	MR headset	Haptic devices	Field	Task
Body mechanics, maintaining balance, quick reaction time, hand-eye coordination, agility, ability to assess potential hazards visually	Vrtual workplace environment (e.g., construction site, factory)	Microsoft HoloLens	Haptic vest (bHaptics TactSuit X40)	Architectural, Civil, Electrical, Industrial, Mechanical Engineering	Safety and risk management

TABLE 4 | Output for the learning scenario in OSHA training.

Human		Technology		Interaction	
Learning	Kinesthetics	Function	Simulation	Application	Motor training, wayfinding, inspecting
Cognitive ability	Spatio-temporal	Feedback	Vibrotactile	Contact	Object, physical phenomenon, process
Awareness	Kinesthetic, proprioceptive, spatial	Actuator principle	Electromagnetic	Spatial-temporal parameter	Space constraint, space dimensions, position, distance, orientation, time, duration, motion
Perception	Pressure, pain, touch motor coordination	Design type	Wearable	Physical parameter	Temperature (through visual perception), size, shape, location, weight, force (deformation resistance)
Sensing medium	Tissue simulation via deformation, muscle contraction	System function	Closed-loop interaction for real-time control and response (haptic sensing devices to virtual elements, from feedback components to tactile sensations) manual		
		Level of immersion	Mixed reality		

4.2.2 | Learning Scenario Description

The study introduces a MR environment with real-time haptic feedback to simulate hazardous workplace conditions and teach OSHA safety standards. By combining visual overlays in MR with physical sensations from haptic devices, learners can engage in a highly immersive experience that simulates real-world safety risks. Trainees navigate through a virtual construction site or factory setting, identify unsafe conditions, and respond appropriately by physically interacting with safety tools. This approach helps learners internalize safety protocols, increasing their awareness and emergency reaction times.

4.2.3 | Revision for Improvement

Revising the learning process flow through the H-HTI framework reveals several areas for potential improvement:

- *Enhancing interactivity*: Improvement can be made by introducing a haptic feedback vest for a more realistic sensation of manipulating safety equipment.
- *Additional types of haptic feedback*: Incorporating visual feedback for temperature representation (e.g., using color codes like red to indicate hot surfaces and chemicals) can effectively simulate heat-related hazards. This visual approach will enhance the multisensory experience and improve trainees' awareness of hazards.
- *Mixed Reality:* Transitioning to MR could enhance the immersive quality by allowing learners to interact with their body movements in the physical environment and virtual objects seamlessly in the virtual environment.

Once these potential improvements have been identified, researchers can assess which enhancements are practical and achievable to meet the learning objectives. Suggestions that are not immediately implementable can guide future research and development.

4.2.4 | Learning Outcomes and Usability Assessment

The assessment of the MR platform evaluates the overall experience based on user feedback on presence, immersion, usability, and skill application. For aspects related to the functionality of haptic cues, trainees will assess the utility of haptic technology in identifying hazards and responding appropriately. Performance metrics, such as response time, error rates in hazard identification, and accuracy in following safety protocols, provide objective insights into the effectiveness of the learning scenario. The study underscores the significant potential of MR and haptic feedback to enhance trainees' perception of safety hazards that may not be immediately visible.

The H-HTI framework will assist educators in systematically analyzing specific learning tasks and competencies within various engineering domains to identify the most suitable learning scenarios for haptic technology, ensuring an effective and immersive educational experience.

5 | Discussion

The taxonomical analysis focuses on HTI and envisions applications in engineering learning. This taxonomy outlines and categorizes interaction modalities, sensing medium, and haptic attributes engaged in problem-solving. It also implements the epistemology in cognitive abilities in engineering learning, emphasizing spatial-temporal cognitive abilities as a crucial component when dealing with abstract concepts and visualizations. The objective stands out for its novel connection between the sense of touch and high cognitive reasoning, potentially transforming the approaches to learning by incorporating immersive technologies. The presented investigation reveals its promising potential to improve human and haptic technology interaction in various contexts related to STEM.

According to the cluster analysis of 40 related papers (see Table A1), the most common areas for applying haptics to engineering are training, education (e.g., physics and chemistry simulations), and automation and robotics. Experimental work on haptics in learning pivots on understanding subjects' responses to haptic feedback. It involves the exploration and manipulation of complex 3D models to improve their spatial reasoning and abstract concept comprehension. In engineering learning tasks, haptic technology provides students with hands-on experience in virtual simulations, allowing them to feel the forces and dynamics of objects they design or work on. Likewise, in vocational training programs, haptics is implemented to simulate various job environments and provide realistic experiences, such as handling heavy machinery, tools, or equipment. In the construction industry, for example, haptic devices, which are applied to remote-controlled construction robots, enable human operators to sense the surface texture, weight, and resistance of the manipulated materials [110]. Overall, the prior research demonstrates that learning through immersive technologies incorporating haptics can enhance knowledge retention and engagement, facilitate skill acquisition, promote safety, increase accessibility, and demonstrate efficacy.

Also, an immersive environment provides a learning benefit in highly complex or conceptual problems that require spatial understanding and visualization. Recent findings of Fokides and Antonopoulos [111] indicated that the immersive experience provided by VR applications, the perceived quality of graphics, feedback, and content, in conjunction with increased interaction and motivation, positively influenced learning outcomes. Following this, to support multisensory learning with haptics, an education model should include two measurements: outcome (knowledge and skills, acquisition, and retention) and experience (learner motivation, engagement, and immersion) [7, 112]. As haptic interventions progress, there will be a substantial transformation in traditional learning and training methods, moving toward a more holistic approach to integrating sensory knowledge acquisition.

5.1 | Future and Trends of HTI

Based on the examination of the literature (Table A1) and the thorough evaluation of the findings, the authors expect the following trajectory of advancements in engineering learning.

Modern haptic tools are transforming into more compact, lightweight, and portable devices, enabling seamless integration into diverse learning environments. The progress of computing technology will result in the creation of more sophisticated haptic suits and exoskeletons that will be able to reproduce a variety of physical sensations, such as texture, pressure, temperature, force, and resistance, delivering realistic high-fidelity feedback. This advancement will allow humans to seamlessly integrate complex sensory interactions with both the physical and digital environments, thereby promoting more holistic and intuitive computing systems.

Haptic technology is expected to move toward full integration into mixed-reality simulations. Learners will be able to interact with digital replicas of engineering systems by incorporating tangible objects from the real world and providing the illusion of physical manipulations, which will lead to more natural forms of interaction.

Eventually, a combination of the senses of vision, touch, sound, smell, and taste into a unified experience will not only streamline motor responses but also liberate valuable cognitive resources, enabling a more focused and efficient problem-solving process.

Haptic technology is becoming more explicitly oriented toward education, aiming to create precise, realistic, and intuitive haptic feedback to allow a solid approach to solving complex engineering problems. Improvements in haptic technology strive to enhance students' spatial and temporal cognitive skills, which are crucial for learning engineering. As a result, we anticipate a wider range of applications that will expand learners' cognitive abilities by establishing digital interfaces for interacting with spatiotemporal parameters that serve to better understand the meanings and purposes of design components in engineering, such as sequences and hierarchies in planning. Mainly, learners will be able to manipulate complicated temporal sequences in physical experiments, explore hierarchical structures in engineering systems, and understand scheduling challenges in real-world project management scenarios.

Technological and scientific progress will lead to more advanced haptic algorithms adapted to individual learning abilities, utilizing machine learning and artificial intelligence to personalize haptic feedback and increase learning outcomes. An example is the convergence of insights from cognitive and computer sciences is driving significant advancements in STEM fields toward the emergence of brain-computer interfaces (BCI) or smartbrain technology. There is a promising trend in using haptic devices for BCI to promote brain plasticity mechanisms [113]. According to the findings of Fleury et al. [114], combining haptic feedback with BCI is going to establish a direct channel for brain-to-device communication, bypassing traditional sensory and motor pathways to track human metrics to monitor user metrics and deliver tailored haptic feedback, thereby optimizing its utilization in engineering applications.

Ultimately, the continuous growth of haptic-augmented HTI will pave the way for advances in problem-solving and its integration into more applications, enhancing the learning experience and refining comprehension of complex ideas and concepts.

5.2 | Research Challenges and Limitations

Future research directions must address the current challenges to allow sustained progression of haptic HTI in engineering learning.

As haptic technology is still in its early stages of development, ongoing technological advancements should expand its applications within engineering. Haptics presently finds more extensive use in medical rehabilitation, but it is anticipated to have a broader adaptation across various engineering fields.

To create a multisensory learning experience, haptic technology necessitates integration with other XR technologies, which requires efficient interfaces and communication protocols between various systems.

At this point, the taxonomy delineates categories of haptic technology by outlining currently available market options alongside customized haptic devices. However, given the rapid technological development, this categorization evolving conceptual cluster—that is, the taxonomy anticipates an expansion in the array of haptic feedback types and actuators, reflecting the ongoing innovation within this domain.

Categorizing the human component, it was challenging to distinguish and explicitly classify the human tactile senses because of the controversial research on the human perception of touch. While the number and categorization of human senses are debated in the literature, most agree that the Aristotelian view of only five senses is incomplete [115]. Many describe "additional" senses such as proprioception (sense of space), nociception (sense of pain), or thermoreception (sense of temperature) [116] as also represented in the taxonomy for which we used the categorization system that it was deemed appropriate for the scope of the taxonomy. Therefore, the authors considered the most common understanding of human perception from the perspective of its application by haptic technology.

Due to the relative novelty of the field, human cognitive abilities, including spatial-temporal reasoning, are not a completely investigated area. The proposed taxonomy serves as a blueprint to incorporate new insights as new research on cognitive abilities unfolds.

It is critical to systematically assess the efficacy of haptic HTI in engineering education to provide insights into learning outcomes in different contexts. Thus, an interdisciplinary collaboration among engineering, cognitive science, computer science, and education researchers is crucial to addressing these issues.

5.3 | Limitations in HTI

To fully integrate haptic technology into educational environments, several key limitations must be addressed.

One major challenge is the high *cost* of advanced haptic devices, which can be prohibitive for institutions with limited budgets. Many haptic systems, especially those with immersive MR integration, require expensive hardware and incur ongoing costs for maintenance, software licensing, and potential upgrades, posing a significant financial burden [49]. To address this, cost-effective alternatives (with a lower immersion level) should be explored, such as leveraging widely accessible devices like smartphones with built-in haptic feedback and AR applications [117].

Availability issues present another significant barrier. Many haptic devices have yet to be readily available as off-the-shelf solutions and often require customization and advanced technical knowledge for deployment. The limited availability of devices also impacts overall accessibility. Market-ready and off-the-shelf devices should be incentivized when designing haptic technology solutions.

Compatibility with standard educational technology reduces opportunities for broader adoption. For example, integrating existing learning environments can be challenging due to compatibility with standards with other MR software and hardware, making it difficult for educators to incorporate haptic technology effectively [50]. Developing standardized guidelines and protocols and simplifying integration into diverse educational infrastructures is crucial to overcoming these barriers [49]. Training resources for educators can also support smoother adoption and reduce the technical burden.

Sustainability is another concern, particularly regarding the ability to keep up with technological advances and ensure compatibility with newer software and hardware [118]. Like other evolving technologies, haptic technologies require upgradeability. The firmware and hardware may perform poorly after new technologies and advancements arrive in the ecosystem, posing financial challenges for institutions seeking to maintain state-of-the-art educational environments. Developing modular and upgrade-friendly haptic systems can help ensure longevity, minimize the need for frequent replacement, and keep costs manageable over time.

Scalability also remains a fundamental limitation, especially in large educational settings. The cost of producing, deploying, and maintaining haptic devices hinders their widespread use, particularly in underfunded institutions [119]. To enhance scalability, innovation is needed to reduce production costs without compromising quality. Developing modular, easy-to-integrate haptic systems seamlessly fitting into existing educational infrastructures will facilitate broader adoption. Haptic systems must also be adaptable to different learning scenarios and subjects, ensuring flexibility across various educational contexts.

Another challenge is maintaining *hygiene* for haptic devices, particularly wearables [120]. In educational environments where devices are shared among multiple users, keeping equipment clean is essential to prevent the spread of bacteria. This can be a significant challenge, especially when funding for high-quality maintenance is limited. To address this, haptic devices should be designed with easily cleanable materials, and clear protocols for cleaning and sanitization should be provided.

In conclusion, to effectively integrate haptic technologies into education, it is essential to address these challenges—cost, deployment and availability, scalability, sustainability, and hygiene—through innovative solutions, standardized guidelines, and educational support.

6 | Conclusions

The use of haptics in engineering education is a novel and still developing field that has yet to reach its full potential. Pioneer works show promising potential for improving HTI in various STEM fields. Advancements in haptic technology can transform the conventional learning and training approaches by introducing immersive, hands-on tools. Further research and development in haptic technology are crucial to improve knowledge retention, increase engagement, facilitate skill acquisition, ensure safety, expand accessibility, and validate its effectiveness in various educational contexts.

This research contributes to engineering learning by studying haptic technology through a *comprehensive review* of haptics applications in engineering education. The findings highlight the numerous benefits of learning with haptic technology. The study proposed a *taxonomical model*—H-HTI taxonomy—as a robust and scientifically grounded framework for understanding how haptic technology can facilitate learning in STEM fields. The taxonomy serves as a model for analysis of haptic feedback to improve understanding of abstract concepts and provide hands-on experiences in virtual simulations, illustrating the value of the technology as an intervention for both students and educators. The taxonomy delves into the fundamental relationships between learning, users, and technology, focusing on haptic applications. It provides valuable insights into H-HTI tailored explicitly to engineering learning. The model results from a detailed analysis of haptic applications in STEM over the past two decades, including a classification of papers based on haptic technology integration.

The H-HTI taxonomy provides a structured framework into three distinct categories: *human, technology, and interaction.* Each category includes a full-spectrum overview of interaction modalities, immersive technologies, and learning methodologies, emphasizing their relevance to engineering education.

The taxonomy relies on the *neurophysiological and cognitive aspects* of the human body, hence providing a more inclusive and holistic approach to designing learning approaches. It can help researchers and educators identify the most effective interaction modalities, methods, technologies, and devices for different learning scenarios. In such scenarios, a comprehensive list of attributes can act as a point of reference, allowing for a gradual refinement of choices to fit the specific needs of the learning settings. The taxonomy can serve as a roadmap for researchers and practitioners to determine the technological aspects of haptic learning approaches to enhance students' knowledge acquisition.

The H-HTI taxonomy is designed to be *scalable*, supporting the gradual integration of haptic technologies based on available resources and infrastructure [121, 122]. In traditional classroom settings, the taxonomy serves as a guide for incorporating haptic feedback into labs and hands-on activities, enhancing students' sensory and practical learning experiences. For larger-scale implementations, haptic-enabled simulations can be utilized in virtual environments, allowing students to access immersive, hands-on experiences irrespective of their physical location [123].

The taxonomy promotes flexibility, allowing applications across different learning environments, from traditional in-person settings to fully online and hybrid scenarios. This *adaptability* makes it feasible to integrate haptic technologies into online learning and distance education contexts, where students can benefit from the sensory engagement provided by haptic feedback. By leveraging cloud-based infrastructure and providing accessible tools and support, the framework aims to ensure that haptic technology can consistently enhance learning outcomes, regardless of the learning setting or the availability of technical support [122].

Comprehensive guidelines and documentation are essential to facilitate scalability and adaptability across different educational contexts, including online and distance education. Publicly accessible platforms such as GitHub can host these resources, making them available to educators and institutions lacking a dedicated technical support team. Detailed deployment guides, example code, and instructional materials will help individual users implement haptic technologies effectively without needing specialized technical expertise [124].

Pilot programs are crucial for validating the effectiveness of the H-HTI framework, focusing on how integrated visual-tactile experiences can enhance students' ability to interpret and apply complex information in problem-solving tasks. By engaging learners in iterative, immersive problem-solving scenarios, such programs can cultivate project engineers equipped with advanced spatial-temporal skills and robust problem-solving capabilities—key attributes for driving innovation and productivity in engineering industries [125].

Building on the emphasis of integrating haptic technology into engineering education, future research can advance in the following directions:

1. Enhancing spatial-temporal cognitive abilities in complex scenarios

   Future studies can explore the application of haptic technology in complex engineering scenarios, such as project scheduling and resource management [126]. Simulating hierarchical sequences and spatial constraints with haptics will help students internalize abstract concepts and improve their decision-making skills [108].

2. Wearable devices for collaborative engineering tasks

   Investigate the use of wearable haptics for team-based engineering projects, where tactile cues can facilitate coordination, enhance communication, and simulate real-world challenges [127]. This approach can further develop students' ability to manage spatial and temporal relationships in collaborative settings.

3. AI-driven personalization in haptic learning

   Incorporate AI algorithms to personalize haptic feedback based on individual learning progress ([128], pp. 21–23). This can optimize the development of cognitive reasoning and ensure that learners are challenged appropriately in mastering both fundamental concepts and applied engineering skills.

4. Evaluating the long-term impact on cognitive skills

   Conduct longitudinal studies to measure how haptic-based learning impacts spatial-temporal cognitive abilities [129] and overall problem-solving proficiency over time [130]. This research will provide evidence of the enduring benefits of H-HTI in education.

The proposed H-HTI framework stands as a beacon, guiding future research endeavors toward a deeper understanding and utilization of haptic technology for developing cognitive reasoning, thereby unlocking new frontiers in engineering education through HTI.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The authors have nothing to report.

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Appendix 1

TABLE A1 | Cluster analysis of papers in the H-HTI framework.

N	Project	Publications	Country	Study design	Application	Haptic learning	Haptic function	Haptic feedback	Design type	Level of immersion	Cognitive ability	Awareness	Perception	Sensing medium	Actuator principle	Robotic control	Contact	ST parameter	Physical parameter
1	Haptic feedback modeling during industrial design practice	Evans et al. [84]	USA	Qualitative	Modeling, creative thinking, learning	Palpability	Simulation	Force, torque	Graspable	2D	Spatial	Cutaneous	Surface profile	Skin touch, muscle contraction, joint movements	Electromag-netic, piezo-electric	None	Object, material	Sequence	Texture, size, shape, deformation resistance
2	Haptic phonemes for haptic communi-cation	Enriquez et al. [132]	Canada	Quantitative	Communi-cating, motor training	Haptic code	Guidance	Force, torque	Graspable	2D	Temporal	Cutaneous	Surface profile	Skin touch	Electromag-netic	None	Process	Time, frequency, duration, sequence	Texture
3	Haptic communica-tion between humans and robots	Miyashita et al. [133]	Japan	Quantitative	Communi-cating, machine control	Haptic code	Simulation	Electro-tactile	wearable	None	Spatio-temporal	Cutaneous, propriocep-tive, spatial	Surface profile, touch localization, motor coordination	Skin touch, muscle contraction, joint movements, head movements, body posture	Piezo-electric	Autonomous	Object	Position, distance, orientation, time, duration, motion, frequency, sequence	Location
4	Windows graphical user interface interacting with haptic feedback stylus	Kyung, Lee [43]	South Korea	Qualitative	Creative thinking learning, problem-solving learning	Palpability	Simulation	Vibro-tactile	Graspable	2D	Spatio-temporal	Cutaneous	Touch localization	Skin touch	Electromag-netic	None	Object	Space dimen-sions, space constraints, orientation, sequence	Texture, size, shape, location
5	Virtual assembly and disassembly simulations	Christiand, Yoon [134]	South Korea	Quantitative	Assembling, machine control, problem-solving learning	Dexterity	Guidance	Force, torque	Graspable	2D	Spatio-temporal	Kinesthetic	Resistive force, touch localization, motor coordination	Muscle contraction, joint movements	Electromag-netic, piezo-electric	Manual	Process	Space dimen-sions, space constraints, position, distance, orientation, time, duration, motion, sequence	Shape, size, location
6	Interactive pipeline	Karkoub et al. [92]	Qatar	Quantitative	Inspecting, motor training	Kines-thetics	Simulation	Force	Graspable	VR	Spatio-temporal	Kinesthetic, propriocep-tive, spatial	Resistive force, touch localization,	Muscle contraction, joint	Electromag-netic	Manual	Object, process	Space dimen-sions,	Size, shape, location

(Continues)

TABLE A1 | (Continued)

N	Project	Publications	Country	Study design	Application	Haptic learning	Haptic function	Haptic feedback	Design type	Level of immersion	Cognitive ability	Awareness	Perception	Sensing medium	Actuator principle	Robotic control	Contact	ST parameter	Physical parameter
	inspection VR system												balance, spatial orientation, motor coordination, locomotion	movements, head movements, body posture				space constraints, position, distance, orientation, time, duration, motion	
7	Haptic virtual reality system for assembly planning and evaluation	Karkoub et al. [92]	Mexico	Quantitative	Assembling, motor training	Dexterity	Simulation	Force, torque	Graspable	2D	Spatio-temporal	Kinesthetic	Resistive force, touch localization, motor coordination	Muscle contraction, joint movements	Electromag-netic, piezo-electric	None	Object, process	Space dimen-sions, space constraints, position, distance, orientation, motion, sequence	Size, shape, weight, location, deforma-tion resistance, force
8	An interactive virtual control laboratory using a haptic interface for undergraduate engineering students	Gonzalez-Badillo et al. [88]	Iran	Qualitative	Fundamen-tal science learning	Kines-thetics	Simulation	Force, torque	Graspable	2D	Spatio-temporal	Kinesthetic	Resistive force, touch localization	Muscle contractions, joint movements	Electromag-netic	None	Object, physical phe-nomenon	Space dimen-sions, space constraints, distance, orientation, time, duration, motion, frequency	Size, shape, location, deforma-tion resistance, force
9	Training representa-tional competence through visual-haptic simulations	Amirkhani, Nahvi [135]	USA	Qualitative	Fundamen-tal science learning	Kines-thetics	Simulation	Force, torque	Graspable	2D	Spatio-temporal	Kinesthetic	Resistive force	Muscle contraction, joint movements	Electromag-netic	None	Physical phe-nomenon	Frequency, motion	Force
10	Generating haptic textures with a vibrotactile actuator	Magana, Balachandran [136]	Denmark	Qualitative	Prototyping	Palpability	Simulation	Vibro-tactile	Touchable	2D	Temporal	Cutaneous	Surface profile	Skin touch	Electromag-netic, piezo-electric	None	Material	Duration, frequency	Texture
11	Kinesthetic haptic interface with controllable force feedback	Strohmeier, Hornbæk [18]	South Korea	Quantitative	Prototyping	Kines-thetics	Simulation	Force	Touchable	VR	Spatio-temporal	Kinesthetic, spatial	Resistive force, touch localization	Muscle contraction, joint movements	Electromag-netic	None	Object	Duration	Resistance, weight, location

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TABLE A1 | (Continued)

N	Project	Publications	Country	Study design	Application	Haptic learning	Haptic function	Haptic feedback	Design type	Level of immersion	Cognitive ability	Awareness	Perception	Sensing medium	Actuator principle	Robotic control	Contact	ST parameter	Physical parameter
	by using hapticdrone																		
12	Providing haptics in virtual reality through quadcopters	Muhammad et al. [46]	USA	Qualitative	Prototyping	Palpability	Simulation	Force	Touchable	VR	Spatio-temporal	Kinesthetic, spatial	Touch localization	Skin touch	Electromagnetic	None	Object	Position, distance, orientation, motion	Shape, size, location, deformation resistance
13	XR learning technologies for learning science	Hoppe et al. [47]	USA	Qualitative	Fundamental science learning	Kinesthetics	Simulation	Force	Graspable	MR	Spatio-temporal	Kinesthetic	Touch localization	Muscle contraction, joint movements	Electromagnetic	None	Object, physical phenomenon	Space dimensions, space constraints, orientation, time, duration, sequence	Shape, size, location, force
14	Bi-manual haptic interface for skill acquisition in surface mount device soldering	Hite et al. [137]	India	Quantitative	Motor training	Dexterity	Guidance	Force, vibrotactile	Graspable	2D	Spatio-temporal	Kinesthetic	Resistive force, touch localization, motor coordination	Muscle contraction, joint movements	Electromagnetic, piezoelectric	None	Process	Distance, orientation, time, duration, sequence	Size, shape, location
15	Haptic virtual welding torch control system using 3D printing	Jae-Hyung et al. [24, 87, 131]	South Korea	Quantitative	Motor training	Dexterity	Guidance	Vibrotactile	Graspable	VR	Spatio-temporal	Kinesthetic	Resistive force, touch localization, motor coordination	Muscle contraction, joint movements	Electromagnetic	None	Process	Distance, orientation, time, duration, sequence	Size, shape, location
16	Vibrotactile and force haptic feedback for task-based presence and performance in VR	Jae-Hyung et al. [87]	Germany	Mixed	Motor training	Kinesthetics	Simulation	Vibrotactile, force	Wearable	VR	Spatio-temporal	Kinesthetic, proprioceptive, spatial	Resistive force, touch localization, balance, spatial orientation, motor coordination, locomotion	Muscle contraction, joint movements, head movements, body posture	Electromagnetic	None	Object, process	Space dimensions, space constraints, position, distance, orientation, time, duration, motion	Size, shape, location, deformation resistance, force
17	Pseudo-haptic effect for learning with touchscreen interaction	Julian et al. [29]	Japan	Quantitative	Fundamental science learning	Palpability	Simulation	Vibrotactile, pseudo haptics	Graspable	2D	Temporal	Cutaneous	Surface profile	Skin touch	Electromagnetic	None	Material	Frequency, duration	Texture

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TABLE A1 | (Continued)

N	Project	Publications	Country	Study design	Application	Haptic learning	Haptic function	Haptic feedback	Design type	Level of immersion	Cognitive ability	Awareness	Perception	Sensing medium	Actuator principle	Robotic control	Contact	ST parameter	Physical parameter
18	Coordinated control paradigm for hydraulic excavator with haptic device	Ujitoko et al. [138]	Italy	Mixed	Machine control, motor training	Kinesthetics	Teleoperation	Force	Graspable	VR	Spatio-temporal	Kinesthetic, proprioceptive, spatial	Resistive force, touch localization, spatial orientation, motor coordination	Muscle contraction, joint movements, head movements	Electro-dynamic, electromagnetic	Manual	Process	Space dimensions, space constraints, position, distance, orientation, time, duration, motion, frequency, sequence	Location, deformation resistance, force
19	Skin-integrated wireless haptic interfaces for VR and ar	Morosi et al. [86]	China	Qualitative	Prototyping	Palpability	Teleoperation	Vibrotactile	Wearable	AR, VR	Spatio-temporal	Cutaneous, proprioceptive	Surface profile, pressure, touch localization, motor coordination	Skin touch, tissue deformation	Electromagnetic	Manual, semiautonomous	Object	Position, distance, orientation, motion	Texture, size, shape, location, deformation resistance
20	Visuo-haptic simulation in learning (physics)	Xinge et al. [139]	USA	Quantitative	Fundamental science learning	Kinesthetics	Simulation	Force, torque	Graspable	2D	Spatio-temporal	Kinesthetic	Resistive force	Muscle contraction, joint movements	Electromagnetic	None	Physical phenomenon	Space dimensions, space constraints, distance, orientation, time, duration, motion	Size, shape, location, weight, deformation resistance, force
21	The virtual electric machines laboratory v-lab	Yuksel et al. [140]	Kuwait	Quantitative	Fundamental science learning	Palpability	Simulation	Vibrotactile	Wearable	VR	Spatio-temporal	Cutaneous, kinesthetic, spatial	Touch localization, spatial orientation, motor coordination	Skin touch, muscle contraction, joint movements	Electro-dynamic, piezo-electric	None	Object, process	Space dimensions, space constraints, position, distance, orientation, time, duration, motion, sequence	Size, shape, location
22	Visuo-haptic simulations to understand the	Hasan et al. [141]	Mexico	Quantitative	Fundamental science learning	Kinesthetics	Simulation	Force, torque	Graspable	2D	Spatio-temporal	Kinesthetic	Resistive force	Muscle contraction, joint movements	Electromagnetic	None	Physical phenomenon	Space dimensions, space	Size, shape, location, weight,

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TABLE A1 | (Continued)

N	Project	Publications	Country	Study design	Application	Haptic learning	Haptic function	Haptic feedback	Design type	Level of immersion	Cognitive ability	Awareness	Perception	Sensing medium	Actuator principle	Robotic control	Contact	ST parameter	Physical parameter
	dependence of electric forces on distance																	constraints, distance, orientation, time, duration, motion	deforma-tion resistance, force
23	Augmenting physics education with haptic and visual feedback	Neri et al. [142]	USA	Qualitative	Fundamen-tal science learning	Kines-thetics	Simulation	Force, torque	Graspable	2D	Spatio-temporal	Kinesthetic	Resistive force	Muscle contraction, joint movements	Electromag-netic	None	Physical phe-nomenon	Space dimen-sions, space constraints, distance, orientation, time, duration, motion	Size, shape, location, weight, deforma-tion resistance, force
24	Associative media learning with smartwatches	Qi et al. [143]	Germany	Quantitative	Communi-cating, problem-solving, learning	Haptic code	Guidance	Vibro-tactile	Wearable	2D	Temporal	Cutaneous	Pressure	Skin touch, tissue deformation	Electromag-netic	None	Process	Time, frequency, duration, sequence	Texture
25	Creating haptic learning environments. novice hapticians design	Rödling et al. [94]	Canada	Qualitative	Prototyping, problem-solving learning	Kines-thetics	Simulation	Force, torque	Graspable	2D	Spatio-temporal	Kinesthetic	Resistive force	Muscle contraction, joint movements	Electro-magnetic	None	Object, physical phe-nomenon	Distance, orientation, time, duration, motion, frequency	Size, shape, weight, deforma-tion resistance, force
26	Training motor skills by virtual insertion task with haptic feedback	Seifi et al. [144]	Japan	Quantitative	Motor training	Dexterity	Simulation	Force	Graspable	2D	Spatio-temporal	Kinesthetic	Resistive force, motor coordination	Muscle contraction, joint movements	Electromag-netic	Manual	Physical phe-nomenon	Position, distance, orientation, time, duration, motion, frequency	Deforma-tion resistance, force
27	Haptic input devices for vr using quadcopters	Takagi et al. [145]	Germany	Mixed	Prototyping	Dexterity	Simulation	Force	Touchable	VR	Spatio-temporal	Cutaneous, kinesthetic, spatial	Touch localization	Skin touch, muscle contraction, joint movements, head movements, body posture	Electromag-netic	None	Object	Position, distance, orientation, motion	Shape, size, location, deforma-tion resistance
28	Soft material technologies	Auda et al. [146]	USA	Qualitative	Prototyping	Palpability	Simulation	Vibro-tactile	Wearable	VR	Temporal	Cutaneous	Surface profile,	Skin touch, tissue	Piezo-electric,	None	Object, physical	Frequency, duration	Texture, size, shape,

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TABLE A1 | (Continued)

N	Project	Publications	Country	Study design	Application	Haptic learning	Haptic function	Haptic feedback	Design type	Level of immersion	Cognitive ability	Awareness	Perception	Sensing medium	Actuator principle	Robotic control	Contact	ST parameter	Physical parameter
	with haptic feedback												pressure, touch localization	deformation, pain	capacitive, shape memory alloy		phenomenon		location, deformation resistance
29	Human-aware motion planning with haptic feedback devices for communicating planned trajectory	Biswas, Visell [147]	Czech Republic	Mixed	Machine control, communicating	Palpability	Teleoperation	Vibrotactile	Graspable	none	Spatio-temporal	Cutaneous, kinesthetic, proprioceptive, spatial	Touch localization, spatial orientation, motor coordination	Skin touch, muscle contraction, joint movements	Electrodynamic, piezoelectric	Semiautonomous	Object, process	Space dimensions, space constraints, position, distance, orientation, time, duration, motion, sequence	Size, shape, location
30	Rendering haptic sensations via chemical stimulants	Grushko et al. [93]	USA	Qualitative	Prototyping	Palpability	Simulation	Microfluidics	Wearable	VR	Spatio-temporal	Cutaneous, proprioceptive, spatial	Temperature, pain	Free nerve endings stimuli, skin touch, pain	Electromagnetic	None	Object, physical phenomenon	Space dimensions, space constraints, distance, orientation, time, duration, motion, frequency	Temperature, chemicals, location,
31	"hapkit," a low-cost, open-source kinesthetic haptic device for use in educational applications	Lu et al. [104]	USA	Mixed	Fundamental science learning	Kinesthetics	Simulation	Force, torque	Graspable	2D	Spatio-temporal	Kinesthetic	Resistive force	Muscle contraction, joint movements	Electromagnetic	None	Object, physical phenomenon	Distance, orientation, time, duration, motion, frequency	Size, shape, weight, deformation resistance, force
32	Communicating inferred goals with passive augmented reality and active haptic feedback	Morimoto et al. [148]	USA	Mixed	Machine control, communicating	Dexterity	Teleoperation	Vibrotactile, force	Wearable	AR	Spatio-temporal	Kinesthetic, spatial	Pressure, resistive force, touch localization, spatial orientation, motor coordination	Tissue deformation, muscle contraction, joint movements, head movements	Electromagnetic	Semiautonomous, autonomous	Object, process	Space dimensions, space constraints, position, distance, orientation, duration, motion	Size, shape, location, deformation resistance, force

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TABLE A1 | (Continued)

N	Project	Publications	Country	Study design	Application	Haptic learning	Haptic function	Haptic feedback	Design type	Level of immersion	Cognitive ability	Awareness	Perception	Sensing medium	Actuator principle	Robotic control	Contact	ST parameter	Physical parameter
33	Manipulation to train construction workers and inspection by hand motion tracking technology and snap-to-fit function	Mullen et al. [149]	USA	Mixed	Assembling, inspecting, problem-solving learning	Dexterity	Guidance	Vibro-tactile	Graspable	AR, VR	Spatio-temporal	Kinesthetic, propriocep-tive, spatial	Resistive force, touch localization, spatial orientation, motor coordination	Muscle contraction, joint movements, head movements	Electromag-netic	None	Process	Space dimen-sions, space constraints, position, distance, orientation, time, duration, motion, sequence	Shape, size, location
34	Vis-hapt: a methodology proposal to develop visuo-haptic environments in education 4.0	Noguez et al. [123]	Mexico	Mixed	Fundamen-tal science learning	Kines-thetics	Simulation	Force	Graspable	2D	Spatio-temporal	Kinesthetic	Resistive force, touch localization	Muscle contraction, joint movements	Electromag-netic	None	Physical phe-nomenon	Space dimen-sions, space constraints, position, distance, orientation, time, duration, motion	Size, shape, location, weight, force, deforma-tion resistance
35	Hapticbots: distributed encountered-type haptics for vr with multiple shape-changing mobile robots	Suzuki et al. [150]	USA	Mixed	Prototyping	Palpability, kines-thetics	Simulation	Force	Touchable	VR	Spatial	Cutaneous, kinesthetic, spatial	Surface profile, resistive force, touch localization, spatial orientation	Skin touch, muscle contraction, joint movements	Electromag-netic	None	Object	Orienta-tion, distance, position	Shape, size, location, deforma-tion resistance
36	A learner-centered approach for designing visuohaptic simulations for conceptual understanding of structures	Walsh et al. [151]	USA	Quantitative	Fundamen-tal science learning	Kines-thetics	Simulation	Force	Graspable	2D	Spatio-temporal	Kinesthetic	Resistive force, touch localization	Muscle contraction, joint movements	Electromag-netic	None	Physical phe-nomenon	Orienta-tion, motion, frequency, sequence	Force, location
37	VR-based training on human-robot interaction for remote	Adami et al. [26]	USA	Quantitative	Machine control, motor training	Dexterity	Teleo-peration	force	Touchable	VR	Spatio-temporal	Kinesthetic, propriocep-tive, spatial	Resistive force, touch localization, balance, spatial	Muscle contraction, joint movements, head	Electro-dynamic, electromag-netic, piezo-electric	Manual	Process	Space dimen-sions, space constraints,	Size, shape, location

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TABLE A1 | (Continued)

N	Project	Publications	Country	Study design	Application	Haptic learning	Haptic function	Haptic feedback	Design type	Level of immersion	Cognitive ability	Awareness	Perception	Sensing medium	Actuator principle	Robotic control	Contact	ST parameter	Physical parameter
	operating construction robots												orientation, motor coordination, locomotion	movements, body posture				position, distance, orientation, time, duration, motion, sequence	
38	Collaborative teleoperation with haptic feedback for collision-free navigation of ground robots	Coffey, Pierson [90]	USA	Quantitative	Wayfinding, machine control	Kines-thetics	Guidance, teleo-peration	force	Graspable	2D	Spatio-temporal	Kinesthetic, spatial	Resistive force, touch localization, spatial orientation, motor coordination	Muscle contraction, joint movements	Electromag-netic	Autonomous	Process	Space dimen-sions, space constraints, position, distance, orientation, time, duration, motion, sequence	Location
39	User behavior in multisensory immersive experiences with a haptic sleeve and olfaction	Gougeh et al. [152]	Canada	Mixed	Prototyping	Palpability	Simulation	Vibro-tactile	Wearable	VR	Spatio-temporal	Cutaneous, propriocep-tive, spatial	Pressure, touch localization	Skin touch, tissue deformation	Electromag-netic	None	Object	Position, distance, orientation	Location
40	Active haptic guidance using robotic haptic proxies	Williams et al. [91]	USA	Quantitative	Wayfinding, machine control	Kines-thetics	Guidance	Force	Graspable	MR	Spatio-temporal	Kinesthetic, propriocep-tive, spatial	Resistive force, touch localization, balance, spatial orientation, motor coordination, locomotion	Muscle contraction, joint movements, head movements, body posture	Electromag-netic	Autonomous	Process	Space dimen-sions, space constraints, position, distance, orientation, time, duration, motion	Location