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A learner-centered approach for designing visuohaptic simulations for conceptual understanding of truss structures

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Abstract

The purpose of this study was to explore the process of designing a visuohaptic simulation for learning structural analysis following a learner-centered approach (LCD). Our implementation of an LCD approach followed a three-part iterative process: (1) requirements analysis and specification, (2) multimedia application design, and (3) prototype inspection. In designing the learning tasks, we employed a three-phase pedagogical approach of prediction, experimentation, and confirmation. We found that designing a visuohaptic simulation for learning purposes is a complex process that requires considering the learners' building of knowledge from different perspectives (e.g., prior knowledge, nonnormative conceptions, cognitive load, and modalities). A total of 51 participants interacted with the visuohaptic simulation following one of two sequenced approaches: (1) haptic feedback and minimal visual information followed by enhanced visual and haptic feedback, or (2) enhanced visual and kinesthetic feedback followed by enhanced visual and haptic feedback. Results suggest that the visuohaptic simulations promoted learners' exploration of structural analysis concepts, improved their intuition about the forces acting on the member of the structure—compression, tension, and zero-force members, and facilitated knowledge transfer. However, we concluded that our approach did not challenge participants to revise nonnormative conceptions and representational competencies. Implications for teaching and learning of our findings are discussed.

KEYWORDS

embodied learning, learner-centered approach, multimodal learning, visuohaptic simulations

1 | INTRODUCTION

Designing educational tools to promote conceptual understanding is a complex undertaking, especially for science content that involves understanding nontangible or "invisible" physical phenomena involving forces or interfaces [53]. Similar to the design of other innovations, educational innovations need a user-centered approach for their design and implementation [46]. Specifically, the design of computer-mediated educational tools should be guided by research from technological, programming, educational, human–computer interaction, and psychological bodies of knowledge [53]. The bodies of knowledge provide expertise on different aspects of the learners and the use of technology, such as technology-enabled learning environments, seamless interfaces and new forms of interaction, and pedagogical approaches that provide ways for facilitating learning tasks and the means of assessing learning [10,32]. Thus, in this study, we approached the design of a visuohaptic learning activity based on the assumption that focusing on learning and multimedia principles early in the design process will better facilitate the learners achieving the learning goals of the instruction—as opposed to, for example, simply focusing on issues associated with usability.

The purpose of this study is to demonstrate the process of designing a visuohaptic learning activity following a learner-centered design approach [46] that entailed a three-part process: (1) requirements analysis and specification, (2) multimedia application design, and (3) prototype inspection [14]. We focus on the domain of statics because of its relevance as a foundational topic in engineering. Moreover, students' difficulties and nonnormative conceptions in learning in statics have been documented [9,47]. The guiding research question is: "*How can a learner-centered approach be used to design visuohaptic simulations for learning statics?.*" We hypothesized that using a learner-centered approach (LCD) to design the visuohaptic simulation combined with a scaffolded learning approach [43] would help students increase their conceptual understanding of forces and their representational skills, including the drawing of free body diagrams (FBD).

2 | BACKGROUND

Visuohaptic simulation consists of a simulation engine that provides two-way feedback—it shows visual cues, such as fields or moving objects, and it also provides haptic feedback to the user via a robotic-handle that learners use to explore the environment and control it [13,23,58]. The use of visuohaptic simulations has been adopted as a form of multimodal learning environments characterized by combining and coordinating the input of two or more human modalities (i.e., eye gaze, gestures, and body movement) with the output of interface technologies [34]. The use of haptic devices for learning purposes, including the learning of abstract concepts, has been implemented in physics instruction (e.g., [1,20,21,23,30,58]). The goal of designing multimodal learning environments is to avoid the dissociation between human actions and thoughts and the actions required to interact with the interface [35]. Moreover, the underlying idea is that using multiple modalities provide richer feedback to the learner [19].

Research on the use of haptic devices to facilitate students' understanding and learning of abstract concepts related to physical phenomena has shown mixed results [59], mainly because the value of adding the force feedback to a learning activity is not clear. Studies that have adopted quasi-experimental or experimental designs, including a treatment group (i.e., visuohaptic simulation group) as compared with a control group (i.e., traditional simulation group) have often identified that students from both conditions benefit equally from the learning experience. Students from each treatment group demonstrated significant learning gains from pretest to posttest scores, but there were no statistically different learning gains between treatment groups.

Mixed results can be found in research with various levels of schooling, including middle schoolers, students in higher education levels, and postgraduate levels for learning different topics. For instance, at the middle school level, Wiebe and colleagues [55] investigated the value of haptic feedback in virtual environments by comparing the students' performance ($n = 33$) in learning the lever's principle. Wiebe et al. [55] found students performed better on the posttest, but the comparison of pretest and posttest scores resulted in nonstatistically significant learning gains for either condition. Results of the analysis of the interaction with the virtual environment showed that students in the visual condition outperformed students in the haptic and visual condition in solving the exercises. Similar results were identified by Young and colleagues [57] for buoyancy ($n = 87$), as well as Minogue and colleagues [29] for cell biology ($n = 80$).

Examples in higher education investigating the value of adding haptic feedback to virtual environments are found in Park et al. [35] for electrical charges ($n = 38$) and Sanchez et al. [41] for electricity and magnetism ($n = 66$). At the postgraduate education level, Schönborn et al. [44] performed a study with 20 students who learned about protein–ligand interactions, and they found that students in the control condition performed twice the number of actions to obtain a less relevant result than the students in the haptic group. The results were consistent across studies—students in both conditions benefited from their learning (e.g., scores were higher in posttest than in pretest), but the value of adding the force feedback in virtual environments was not conclusive.

Researchers have hypothesized that when presenting visualization and haptic feedback together, the visual information could undermine haptic information intake [12,37]. Others have hypothesized that participants may experience cognitive overload [22,58,59]. Magana et al. [23] proposed a sequenced approach for learning electricity and magnetism with visuohaptic simulations that were applied to a population of 170 undergraduate students who performed four experiments that provided different combinations of visual and haptic feedback: visual (V) feedback only, haptic (H) feedback only, simultaneous visual and haptic (V + H) feedback, and a sequenced modality of haptic feedback first followed by haptic feedback plus visual feedback (H → V + H). Results showed significant learning gains from pretest to posttest for students who received haptic feedback only. For learning about friction, Yuksel and colleagues [58] studied undergraduate students ($n = 48$), comparing the use of a visuohaptic simulation in two different sequenced approaches (enhanced visual to enhanced visual + haptic [V → V + H] vs. haptic to enhanced visual + haptic [H → V + H]). They found statistically significant differences in the comparison of the pretest and posttest scores for each treatment, but no significant differences between the learning gains of the treatments. Walsh and colleagues [51] also compared undergraduate students' scientific explanations of friction concepts before and after using the visuohaptic simulation with a sequenced approach (V → V + H vs. H → V + H). They found statistically significant differences in the comparison of the pretest and posttest scores only in the H → V + H approach. Also, they found that students in the H → V + H approach tended to improve the score of their scientific explanations while students in the V → V + H tended to maintain the score of their scientific explanations (e.g., for answering the role of the object weight in friction, 46.7% of the students in the H → V + H condition improved their score on the posttest, while 42.9% maintained their score in the V → V + H).

In this study, we examined a visuohaptic simulation prototype for learning structural analysis that was designed using a LCD [46]. To investigate the impact of the visuohaptic simulation prototype on undergraduate students ($n = 51$) learning of structural analysis, compared students' pre- and post-test score after engaging in one of two instructional conditions: (1) visuohaptic simulation with a sequenced approach of visual and haptic feedback (V → V + H and H → V + H) or (2) as a computer simulation, without haptic feedback (V).

3 | METHODOLOGICAL APPROACH

A multidisciplinary team of researchers from educational technology, physics education, engineering education, and computer graphics designed the visuohaptic simulation and the supporting protocols. We designed the learning activities following the guidelines of the LCD proposed by Holzinger and Motschnik-Pitrik [14]. The approach suggests three levels for designing educational tools: requirements analysis and specification, multimedia application design, and inspection or evaluation of the prototypes.

3.1 | Level 1: Requirements analysis and specification

The first level of designing educational tools using the LCD approach focuses on the learners, the learning context, the learning content, and the learning goals. Regarding the learners and the learning context, the target population in our study focused on entry-level students in undergraduate Science, technology, engineering, and mathematics (STEM) programs. In general, the entry-level students were 19 years old or younger. The majority of STEM students often have positive attitudes and moderate-to-high achievement in mathematics [6]. This population is also often exposed to STEM courses during high school [3]. The context of the study is a laboratory section of an introductory statics course.

The learning content was statics. Statics is one of the foundational courses in the mechanical and civil engineering undergraduate programs. The use of statics is important in the transition from basic underlying physics concepts (such as torque and equilibrium laws) applied to one body to a complex analysis regarding several bodies or systems of forces. Statics lays the foundation for upper-level courses, such as dynamics and materials, which require mastery of fundamental skills, such as free-body diagrams and working with forces [9].

Steif [47] identified common nonnormative conceptions (nonscientific explanations) in statics may arise in students' explanations of, for example: forces acting between bodies, a combination of bodies and their static equivalence to a force and couple, the equilibrium of bodies, and conditions of contact between bodies implying simplification of forces. Steif [47] also identified basic skills that students should possess regarding knowledge in statics, such as (a) discrimination in separating members of an assembly and how they are interconnected within the structure, (b) discernment between the surfaces of contact and the connected parts and how this impacts the distribution of forces within the structure, grouping different members of an assembly in several ways [31], and (c) tagging forces and couples into consistent graphical representations and variables. Finally, Steif [47] pointed out the importance of

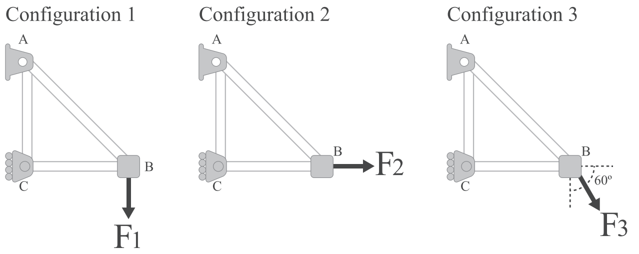

FIGURE 1 External force directions for a three-element truss from Walsh et al. [52].

understanding the shear-moment behavior of straight multispan beams. This basic understanding not only refers to resistance theories and calculation processes but also to understanding the axial, shear, torsion, and bending phenomena for structures subjected to external forces [11]. The main learning goal of the visuohaptic simulation was for students to be able to identify the forces acting on the members of a truss structure, and students to be able to represent through a FBD the force acting on the joints of a truss structure.

Walsh et al. [52] performed a pilot study investigating engineering technology students' conceptual and representational knowledge of structural analysis ($n = 37$). The results suggested that students had fragmented conceptions and representational errors in their FBD regarding the forces acting on a truss structure when a specific external force acted on it in three different directions (Figure 1). In this pilot study, more than 40% of the participants failed to determine the type of force acting on a structural member (i.e., AB, BC, and AC) when an external force was applied on a joint (e.g., compression, tension, or zero-force). Also, more than 70% of the participants failed to draw a scientifically accurate FBD of the joints (i.e., Joint A, Joint B, and Joint C).

3.2 | Level 2: Multimedia application design

Multimedia application design involves identifying the appropriate pedagogy, technology, and affordances that support the learning identified in the requirement analysis and specification. Linear algebra is the traditional mathematical method used for teaching structural analysis [7,18]. Computer simulations are also used as a teaching tool for structural analysis. Using computer simulations as an active learning method has many advantages for learners, including (a) allowing students to test the different configurations of structures and forces easily; and (b) allowing students to focus on specific variables of the system instead of the complete system at the same time [60]. Yet, some computer simulations available for teaching are based on the input and output interaction. Simulations require students to define parameters (e.g., forces or the object sizes) to obtain the results (e.g., forces direction, magnitude), potentially blocking the process of understanding the "how" and the "why" of the results [7].

We first reviewed existing didactical and pedagogical models to perform the multimedia application design of the visuohaptic simulations. Research in educational psychology and learning sciences has resulted in a set of multimedia learning principles [24]. For instance, the multimedia learning principle states that people learn better from words and pictures than words alone [25]. Words and pictures presented together have learning advantages, such as increasing the self-perception of learning [45], deepening and integrating understanding and problem solving, and increasing transfer of learned principles [4]. However, the human capacity to process verbal and nonverbal is limited, and multimedia learning principles encourage active learner cognitive load management.

Our learning environment consisted of a visuohaptic simulation and a worksheet (and associated protocol) that guided participants during the learning process; we considered multimedia principles in the overall design. In their study, Rieber et al. [38] found that using simulations with guidance, instead of discovery learning, benefited students' development of conceptual knowledge. Also, Rieber and colleagues [38] found that alignment between the assessment in modalities and objectives is key for ascertaining students' scientific knowledge. For instance, if the simulation focused on nonverbal information, the evaluation of concepts showed better results when assessed in a nonverbal form.

The structure displayed by the simulation consisted of three joints and three members (see Figure 1). All members (e.g., AB, BC, and CB) are the same length, and their weight is negligible compared to the load. Regarding the joints, Joint A and Joint B are pin joints. Joint A is connected to the ground, and Joint B is not and the load applied to Joint B is 2, 4, 6, 8, or 10 Newtons. The load, F_1, F_2, and F_3 angles were fixed (e.g., F_1 acted in the negative y-direction, F_2 on the positive x-direction, and F_3 at 60° below the positive x-direction). Joint C is a roller joint. The displacement that occurred in the structure is negligible in comparison with the dimension of the truss structure. Table 1 shows the multimedia learning principles considered in the study's learning activity.

The principles that guided the design of the worksheets were sequencing and signaling [26,49,50]. We designed three worksheets corresponding to the phases of the pedagogical approach of prediction, experimentation,

TABLE 1 Principles of multimedia learning and the impact on the study's learning activity

Principle	Element	Application to the design of the learning activity
Sequencing [26,50]	Worksheet, visuohaptic simulation	A truss structure is designed to teach structural analysis. Learners apply the forces (F_1, F_2, and F_3) in a sequenced way that helps students consider the applied force's direction in distributing the truss structure's forces. The worksheet guides the learning activity following the pedagogical approach of prediction, experimentation, and confirmation by White and Gunstone [54]. Before the learning activity, learners should complete a pretraining session where they have the opportunity to learn how to use the haptic device, reducing the novelty effect of the technology and the cognitive load [22].
Redundancy [15]	Visuohaptic simulation	The enhanced visual cues and the haptic feedback provide complementary information on the truss structure's forces. The haptic feedback provided general information of the forces (e.g., direction and magnitude of the forces). The enhanced visual cues show the direction of the forces by color (e.g., tension forces are blue) and by showing the arrow-head. The thickness of the truss members changes according to the magnitude (e.g., the wider, the higher force's magnitude). Enhanced visual cues also show the numerical value of the forces.
Learner control [42]	Worksheet, visuohaptic simulation	Learners had control over their learning process. Learners work individually and at their own pace. The activity was designed to be completed within 60–90 min. Learners interacted with the visuohaptic simulation during a laboratory section of an introductory statics course.
Spatial split-attention [2]	Visuohaptic simulation	Enhanced visual cues and haptic feedback provide the same information for each member of the truss structure. Students focus on one feedback first and then the other (i.e., haptic feedback first, and then visual feedback or vice versa). Free body diagrams are also displayed one by one for each of the joints as students' mouse roll-over specific joints.
Signaling [49]	Worksheet, visuohaptic simulation	The worksheet guides students to focus on specific members and joints. The visuohaptic simulation provides information to determine the force magnitude and direction.
Modality [19]	Visuohaptic simulation	Verbal information is presented with the enhanced visual cues (magnitude value of the forces in Newton). Nonverbal information is presented through haptic feedback. Students can feel the forces applied to the structure, and they can also feel the forces of the members as they are in tension, compression, or zero force. The force magnitude and direction are calculated by using Newton's Laws. The force feedback was provided via a Falcon Novint device with three degrees of freedom and two lbs' force capability.

and confirmation by White and Gunstone [54]. All three worksheets focused on the same concepts and representations of the structural analysis topic.

The prediction phase prompted students' articulation of prior knowledge. Learners wrote their prediction before engaging with the visuohaptic simulation. The experimentation and observation worksheet guided participants through the interaction with the visuohaptic simulation. The worksheets guided students to work individually, at their own pace, and pay attention to specific members of the structure (e.g., member AB in Figure 1). The worksheets included conceptual and representational questions that addressed the effect of an external force acting on two truss's structure-specific joints. For Structure 1 (Figure 1), students determined the external force's effect at different angles (F_1, F_2, or F_3) on the structure's joints and members. For instance, for Configuration 1 of Structure 1, F_1 is an external force acting on Joint B at the negative *y*-direction. Learners determined if the truss members AB, BC, and AC were under tension, compression, or were zero-force members. Also, they drew corresponding FBDs of the forces acting on Joints A, B, and C. Participants repeated these exercises for Configurations 2 and 3 of Structure 1.

FIGURE 2 Visuohaptic learning environment

Redundancy and modality [15,19] were the main considerations for integrating visual and haptic information through the visuohaptic simulation by enabling the students to see and feel the forces. The visuohaptic simulation is a multimodal learning tool that provided two types of feedback: visual and haptic. The screen of a laptop computer showed visual feedback, and the haptic device (Falcon Novint, in our setting) provided haptic feedback (see Figure 2). The visual information that the simulation provided was either "minimal" or "enhanced." Minimal visual cues included only spatial information (e.g., location of the forces), while enhanced visual information provided the minimal visual cues and the force vector information (magnitude and direction of the force).

The haptic feedback provided kinesthetic feedback and force feedback. Kinesthetic feedback included proprioceptive feedback related to space's body position (e.g., how much distance the arm moves and what direction). The force feedback provided information about the magnitude of the forces acting on the structure. The magnitude of the force determined the magnitude of the sensation through the haptic device (e.g., learners felt harder the haptic device's movement when the force acting in the structure's member was higher). The force feedback and the enhanced visual cues can be activated or deactivated.

Sequencing and spatial split-attention principles [26,50] were incorporated during the design of the interaction. Before engaging with the structural analysis topic, the worksheet guided students in a pre-training activity. As part of the pre-training activity, the instructor described the haptic device's function, guided students in the process of using, understanding, and interpreting the feedback provided by the visual cues or the haptic device.

The visual feedback is shown in Figure 3. The minimal visual cues interface (Figure 3a) showed the applied force and the structure, and the enhanced visual cues (Figure 3b) showed the visual representation of the forces (where member thickness corresponds to force magnitude). The size of the arrow was based on the magnitude of the force. Also, the color-code of the arrows indicated the direction of the forces acting on the members (blue indicated tension, yellow indicated compression). Orange arrows indicated reaction forces between the truss and wall. The legend was shown in the control panel of the visuohaptic simulation. The FBD was visible when the students used the computer mouse roll-over joint (no need to use the haptic device). The mouse roll-over modality was implemented under the guidance of the spatial split-attention principle.

The haptic feedback provided information about the magnitude and direction of a force on each member of the structure (i.e., AB, BC, and AC in Figure 4). When participants placed the haptic cursor along a truss member (say, at Location 1 or 2 on Figure 4) and pressed the button on the haptic device, haptic feedback indicated the nature of the force on that truss element. If there was tension in the truss member (Figure 4a,b), the haptic feedback moved the learner's hand toward the joints. If there was compression in the truss member (Figure 4c,d), the haptic feedback moved the learner's hand toward the center of the member. For a zero-force member, the device provides no haptic feedback to the learner and thus no motion to the learner's hand (Figure 4e,f). In addition to the direction of the forces, the learners also feel the magnitude of the forces. A larger force magnitude results in stronger force feedback and faster movement of the haptic device handle.

The sequencing principle [26,50] was reinforced by having students test their predictions with the visuohaptic simulation and providing the possibility of turning on and off the enhanced visual cues and the haptic feedback. Enabling and disabling the enhanced visual cues and the haptic feedback allowed students to follow a sequenced feedback approach [23]. The sequenced approaches allowed students to interact with the visuohaptic simulation two times during the experimentation and observation phase. Students answered the conceptual and representational questions based on the visual or haptic information provided by the visuohaptic simulation during the first interaction. The combinations used for the first interactions were minimal visual information + haptic feedback (H) and enhanced visual information + kinesthetic feedback (V).

During the second interaction, the visuohaptic simulation expanded the conceptual and representational information to students (e.g., by enhancing the visual

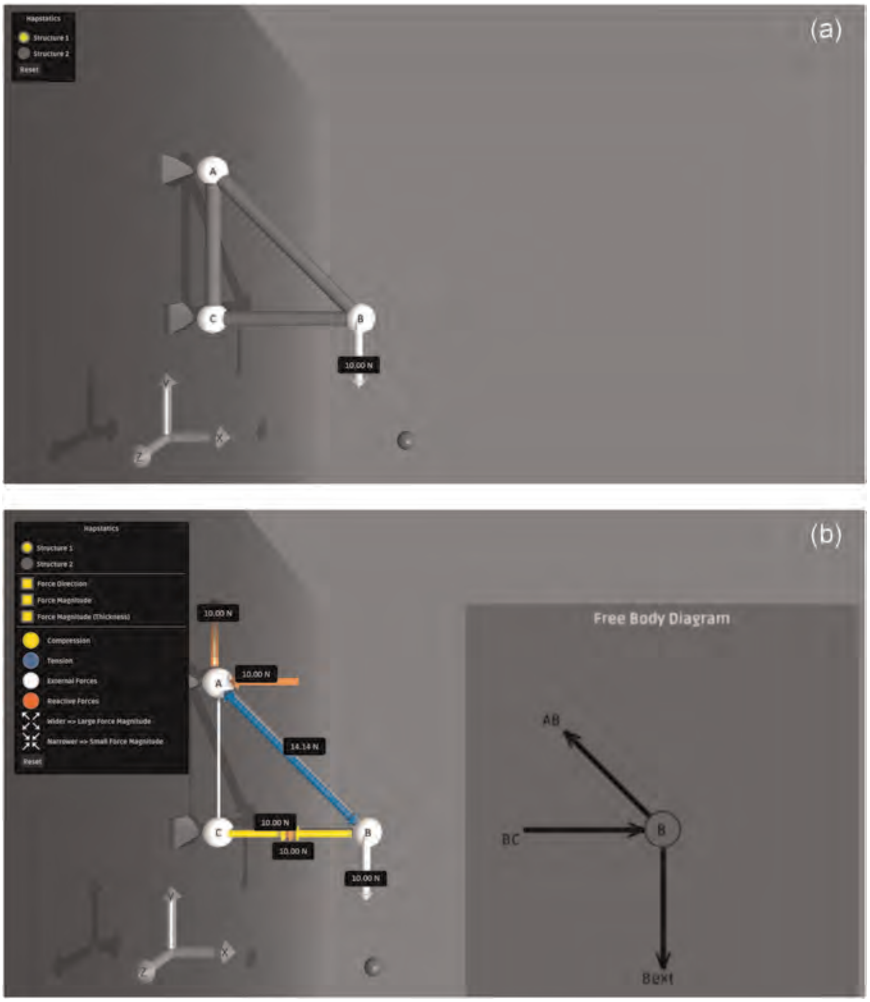

FIGURE 3 Structure 1 with no visual cues (A) and with enhanced visual cues (B)

information or activating the haptic feedback. Students received enhanced visual information + haptic feedback (V + H) in a complementary way (redundancy principle, [15]). The second interaction aimed to promote a revision of the conceptual and representational responses based on the visuohaptic simulation's information. Students were allowed to change and modify their initial responses on the first interaction during their response revision. For instance, in the haptic + minimal visual information to enhanced visual + haptic treatment (H → V + H), students articulated their conceptual and representational responses based on the information provided by the haptic feedback (e.g., perceptual information of the force's magnitude and force's direction) and revised their responses with the information provided by the enhanced visual information. Providing feedback in a sequenced way may help reduce the potential cognitive load experienced by the students [20], provides information about the forces acting on the truss structure through different senses, visual and haptic [23], and promotes positive changes in conceptual knowledge [43,46].

3.2.1 | Summary of the visuohaptic simulation characteristics

Table 2 shows the information provided to learners and how the haptic and visual feedback displayed the information.

In addition to the conceptual information provided by the visuohaptic simulation, virtual environment affordances have been shown to result in learners' improvement in the conceptual understanding of trusses using the visuohaptic simulation—specifically, because of the advantage of a virtual environment in controlling variables to minimize errors [60]. The learners who used the visuohaptic simulation, as mentioned previously, were entry-level undergraduate STEM students with little to no experience with structural analysis. Scaffolding the content information allowed learners to construct knowledge. First, the truss members' weight was negligible compared to the loads applied to the joints (F_1, F_2, and F_3), allowing learners to focus on the effect of the structure's load. Second, the angles of the loads, F_1, F_2, and F_3, were fixed. F_1 only acted in the negative

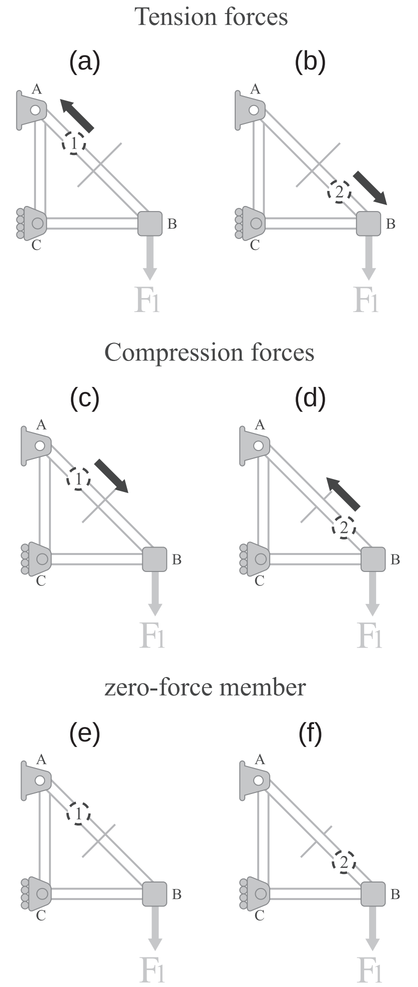

FIGURE 4 Haptic feedback interaction, tension forces (A, B), compression forces (C, D), and zero-forces (E, F)

y-direction, F_2 on the positive *x*-direction, and F_3 at 60° below the positive *x*-direction. The increment of the load was from 0 newtons to 10 Newtons. And thirdly, there was no motion in the truss structure (e.g., rotation or translation movements).

3.3 | Level 3. Evaluation of the prototype

The population selected to evaluate the prototype consisted of 51 first-year students from a mechanical engineering technology undergraduate-level course. The 16-week course took place at a Midwest university in the United States during Fall 2018 and consisted of two lectures of 1 h each and a laboratory session of 2 h/week. Participating students individually completed the study during Week 8 of the semester. Students attended one of the three laboratory sessions available for the course and

TABLE 2 Feedback

Content information	Visual information		Tactile information	
	Minimal	Enhanced (V)	Kinesthetic	Haptic (H)
Applied force to the joints (F_1, F_2, and F_3)	The minimal visual information showed the numerical value and direction F_1, F_2, and F_3. No difference in this aspect for minimal and enhanced visual information.		Learners used the haptic device for applying the force, but learners did not perceive the force magnitude through the sense of touch.	
Forces acting on the joints	The minimal information did not display it.	Learners positioned the mouse of the computer over the joint to display the FBD of the joints.	Learners did not perceive through the sense of touch the forces acting on the joints.	
Forces acting on the members		Learners saw the direction (i.e., arrow) and magnitude (i.e., numerical value and thickness of the truss member) of the forces. The information was color-coded.	Learners felt the haptic device's movement, inwards, outwards, or no movement depending on the type of force acting on the member (Figure 4).	Learners felt the haptic device's movement, inwards, outwards, or no movement depending on the type of force acting on the member (Figure 4). Additionally, learners felt the magnitude of the force through haptic feedback. For instance, the haptic device did a stronger movement for high magnitude force.

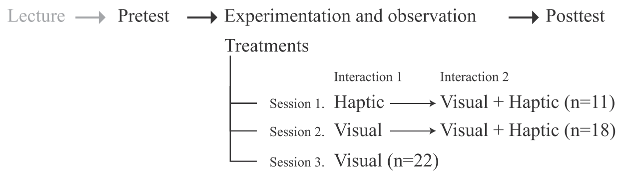

FIGURE 5 Procedures used to evaluate the prototype visuohaptic simulation

were randomly assigned a condition for each laboratory session. Figure 5 shows the procedures.

The evaluation of the prototype consisted of three sequenced phases: (1) pretest, (2) experimentation and observation, and (3) posttest. Students completed the pretest after receiving the structural analysis course lecture but before engaging in the laboratory sessions. During the pretest, participants answered conceptual and representational questions based on their prior knowledge (see Appendix A). The experimentation and observation phase consisted of students testing their prior knowledge with the visuohaptic simulation. During the experimentation and observation phase, participants used the visuohaptic simulation in a sequenced approach ($V \rightarrow V + H$, $H \rightarrow V + H$) or with enhanced visual feedback (V). Finally, the posttest consisted of answering the same conceptual and representational as the pretest.

All phases contained the same explanation-type questions, but during the experimentation phase, participants had the opportunity to answer the questions while interacting with the visuohaptic simulation. For the pretest and posttest, students answered the questions without the visuohaptic learning tool. Students answered questions based on the three configurations of Structure 1 (see Figure 1). Hence, the assessment of Structure 1 responses provided us with information about students' interpretations from the visual and haptic feedback, as well as information for improving the learning tool for future interventions.

The experimentation stage occurred 1 or 2 days after the lecture and the completion of the pretest. The interaction with the visuohaptic simulation took place for 60 min. We randomly assigned the laboratory session conditions ($H \rightarrow V + H$, $V \rightarrow V + H$, and Visual only). Students in Session 1 ($n = 11$) interacted with the visuohaptic simulation in the haptic + minimal visual cues to enhanced visual + haptic sequence ($H \rightarrow V + H$). Students in this condition first interacted with the visuohaptic simulation by receiving haptic feedback and minimal visual cues (i.e., spatial information). Then, during a second interaction, students received both modalities together. Students in Session 2 ($n = 18$) interacted with the visuohaptic simulation in the enhanced visual + kinesthetic feedback to enhanced visual + haptic sequence ($V \rightarrow V + H$). Students in this condition first interacted with the visuohaptic simulation by receiving enhanced visual cues and kinesthetic feedback (i.e., a force vector, direction, and magnitude of the force) and then received both modalities together in the second interaction. Students in Session 3 ($n = 22$) interacted once with the visuohaptic simulation and received only enhanced visual cues + kinesthetic feedback. The different treatments allowed us to investigate the effect of the visual and the haptic feedback in the visuohaptic simulation. For instance, we evaluated the value of the enhanced visual cues and haptic feedback by comparing the first interaction answers. By comparing the second interaction, we evaluated the value of haptic feedback on students who had enhanced visual cues and vice versa. The visual treatment (V) was the only treatment that did not receive haptic feedback. After the interactions, all participants completed a posttest assessment and a final exit survey.

Figure 6 shows the example questions from the pre- and post-test. Question a evaluated students' conceptual knowledge of the forces acting on the members when an external force is applied to a joint in three different configurations (see Figure 1). Students answered Question a for Configuration 2 (F_1 on positive x-direction) and Configuration 3 (F_1 at 60° below the positive x-direction). Question b identified students' representational competence. Students only drew the FBD of the forces acting on the joints for Configuration 1 (F_1 on negative y-direction).

In the process of assessing conceptual responses, we performed two types of analysis. First, we categorized each response as correct or incorrect. When a student correctly answered the three forces acting on the members of the structure, the answer was considered correct. When a student answered at least one force acting on the members incorrectly, the answer was considered incorrect. Table 3 shows the correct answer per configuration.

The second analysis of the conceptual question consisted of assigning points to the answers. For Question a, every correct response received one point, and every incorrect answer received zero points. A maximum of three points could be achieved by correctly responding to the force acting on each configuration's three members. For example, if the student answered that the member AB is under tension when F_1 is applied to joint B in the negative y-direction, the student received one point. Contrary, if the student answered that member AB is under compression or is a zero-force member when F_1 is acting on joint B, the student received zero points. The maximum number of points a student could obtain in the conceptual questions is nine (three configurations, three

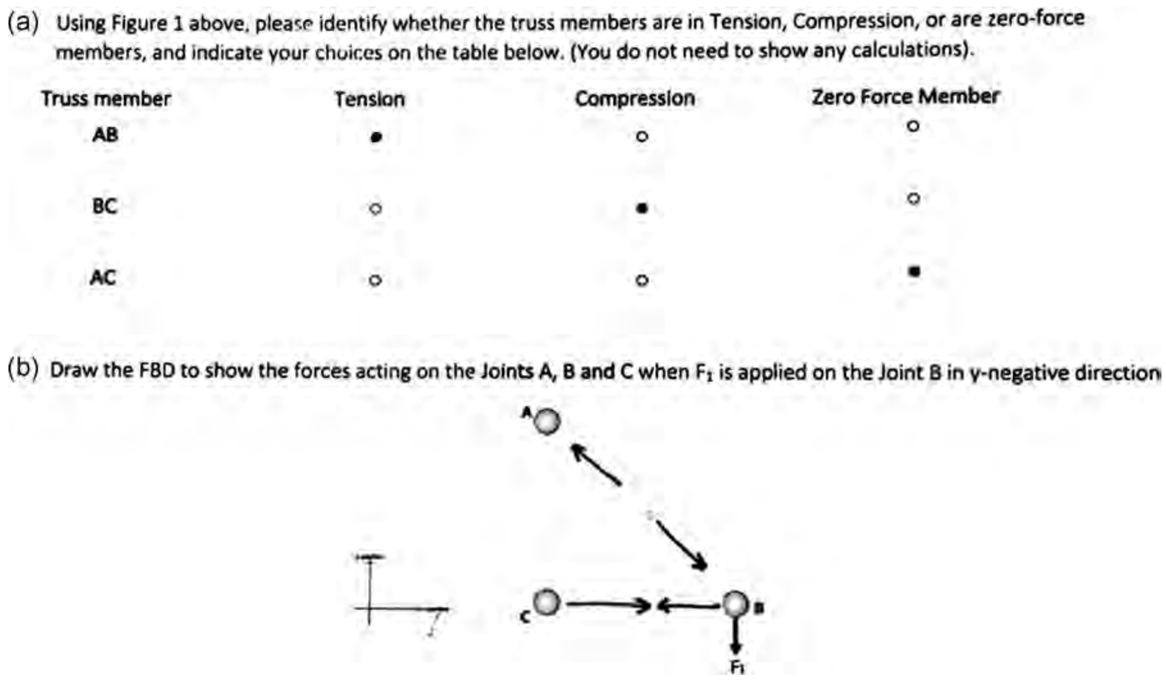

FIGURE 6 Example of the pre- and post-test assessment

TABLE 3 Correct answers of the forces acting on the members per configuration

Member	Configuration of structure 1: Configuration 1 (F_1 on negative y-direction)	Configuration 2 (F_2 on positive x-direction)	Configuration 3 (F_3 at 60° below the positive x-direction)
AB	Tension	Zero-force	Tension
BC	Compression	Tension	Compression
AC	Zero-force	Zero-force	Zero-force

points per configuration). Scores were normalized and compared using descriptive and inferential statistical methods. The descriptive analysis consisted of calculating mean scores and standard deviations. One-way analysis of variance was used for the comparison of the pretest scores and the posttest scores between conditions. A paired t-test was used to determine statistically significant differences between the pretest and posttest scores per condition. The confidence level for all inferential analysis was 0.05, which is the most common value used in educational settings. Moreover, assumptions (e.g., normality and constant variance) of the inferential analysis were investigated, and results showed that the data met the assumptions.

For the classification of the effect sizes, we used the scale provided by Rubin [40], which considered strong effect size when $|d| > 0.8$; moderate to strong effect size when $0.65 < |d| < 0.8$, moderate when $0.4 < |d| < 0.65$; weak to moderate $0.2 < |d| < 0.4$, and weak when $|d| < 0.2$.

3.4 | Effectiveness of the learning experience

3.4.1 | Students' conceptual answers

Students answered the conceptual questions (e.g., Question a in Figure 6) of the three configurations of Structure 1 (see Figure 1). Table 4 shows the classification of correct and incorrect answers.

As shown in Table 4, there was an increment of correct answers in all the configurations from pretest to the experimentation phase and from pretest to posttest. For instance, for answering Configuration 1 (F_1 acting on negative y-direction), the percentage of correct answers increased from pretest to the first experimentation phase (Δ in H → V + H: 36.36%, V → V + H: 55.56%, and V: 40.91%), and from pretest to posttest (Δ in H → V + H: 36.36%, V → V + H: 50%, and V: 45.45%). Configuration 2 (F_1 acting on positive x-direction) had the highest percentage of incorrect answers in the pretest (H → V + H:

TABLE 4 Forces acting on the members

Treatment	N	Confi-guration	Phase of the study (%)							
			Pretest		Experimentation: First interaction		Experimentation: Second interaction		Posttest	
			C	I	C	I	C	I	C	I
H → V + H	11	Conf 1	63.64	36.36	100.00	0.00	100.00	0.00	100.00	0.00
		Conf 2	9.09	90.91	90.91	9.09	100.00	0.00	90.91	9.09
		Conf 3	36.36	63.64	100.00	0.00	100.00	0.00	81.82	18.18
V → V + H	18	Conf 1	44.44	55.56	100.00	0.00	100.00	0.00	94.44	5.56
		Conf 2	0.00	100.00	88.89	11.11	88.89	11.11	55.56	44.44
		Conf 3	27.78	72.22	100.00	0.00	100.00	0.00	55.56	44.44
V	22	Conf 1	50.00	50.00	90.91	9.09	No second interaction		95.45	4.55
		Conf 2	0.00	100.00	86.36	13.64			81.82	18.18
		Conf 3	22.73	77.27	81.82	18.18			59.08	40.91

Abbreviations: C, correct; I, incorrect.

90.91%, V → V + H: 100%, V: 100%), but also showed increment from pretest to the experimentation phase (Δ in H → V + H: 81.82%, V → V + H: 88.89%, and V: 86.36%), and from pretest to posttest (Δ in H → V + H: 81.82%, V → V + H: 55.56%, and V: 81.82%). In Configuration 3 (F_1 acting at 60 degrees below the positive x-direction), the increment from pretest to the first experimentations' phase was (Δ in H → V + H: 63.64%, V → V + H: 72.22%, and V: 59.09%), and from pretest to posttest (Δ in H → V + H: 45.46%, V → V + H: 27.78%, and V: 36.35%).

The experimentation phase analysis shows that the first interaction had a major effect on students' answers during the experimentation stage. For instance, students in the V → V + H treatment did not change their response during the second interaction, even when the answer was incorrect. The students who incorrectly identified the forces acting on Configuration 2 in the H → V + H treatment corrected their answer during the second interaction, with the enhanced visual cues activated.

The main problem identified in the three configurations was that students failed to recognize the zero-force members in Structure 1. Specifically, in Configuration 1, results suggest that students in all phases failed to recognize AC as a zero-force member (Pretest: H → V + H: three students, V → V + H: nine students, and V: nine students; Experimentation: V: one student; Posttest: V → V + H one student, V: one student). In Configuration 2, members BA and AC were zero-force members. Only one student in H → V + H treatment recognized members BA and AC as a zero-force member in the pretest. In all the other phases of the study, students recognized BA and AC as zero-force member.

Similarly, for Configuration 3, students had problems identifying the AC member as zero-force (Pretest: H → V + H: four students, V → V + H: eight students, and V: twelve students; Experimentation: V: one student; Posttest: H → V + H: one student, and V: one student). To further compare the students' performance in the different treatment and phases of the study, we assigned one point to each students' correct answer. Table 5 shows the normalized scores results.

Results suggest improvements from pretest to experimentation (Δ in H → V + H: 29.33%, V → V + H: 37.11%, and V: 34.89%), and from pretest to posttest (Δ in H → V + H: 27.33%, V → V + H: 27.22%, and V: 34.89%). The decrement of scores from the experimentation phase to the posttest in the H → V + H treatment was 2% and 9.89% in the V → V + H treatment. Students in only Visual treatment maintained the mean score of 89.89%.

The experimentation results show that participants ($n = 11$) receiving haptic feedback with minimal visual cues (first interaction of the H → V + H condition) correctly connected the haptic feedback with the type of force experienced by each member in the three configurations of the structure (e.g., tension forces pulled the members from the sides, haptic device moving toward the joints). Only one participant incorrectly indicated that on Configuration 2 (F_1 acting on the positive x-direction), the member AB was under tension instead of being a zero-force member. The participant corrected the answer with the enhanced visual cues activated. Participants in the V → V + H condition were able to identify the tension, compression, and zero force

TABLE 5 Score obtained in Question *a* regarding the forces acting on the members

		Pretest (%)		Experimentation (%) First interaction		Second interaction		Posttest (%)	
Treatment	N	Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*
H → V + H	11	68.67	20.33	98.00	6.67	100.00	0.00	96.00	7.44
V → V + H	18	60.44	15.33	97.56	7.22	97.56	7.22	87.67	10.00
V	22	55.00	23.33	89.89	20.78	No interaction		89.89	17.11

members from the enhanced visual feedback. Incorrect answers in the first interaction were not corrected with the haptic feedback activated during the second interaction.

For the comparison of performance between the treatments, we first compared the pretest scores. Results suggest no statistically significant differences between the treatments, $F(2, 48) = 1.678$, $p = 0.197$. Thus, we proceed to compare performance during and after the use of the visuohaptic simulation. Table 6 shows the normalized results of the comparison between pretest and posttest scores.

Results suggest statistically significant learning between the pretest and posttest scores in all treatments ($p < 0.001$) and strong effect sizes of the visuohaptic simulations in the scores, $|d| > 0.8$. The comparison of posttest scores between the treatments suggest no statistically significant differences, $F(2, 48) = 0.986$, $p = 0.381$. In other words, learners from all treatment benefited similarly from the learning experience with the visuohaptic simulation.

3.4.2 | Students' representational competence

The analysis of students' representations suggests that students had difficulties drawing the forces acting on the joints in Configuration 1 (F_1 acting on negative *y*-direction). Table 7 shows the percentage of correct and incorrect FBD per stage of the study and treatment.

In the pretest, only four students from all sessions (H → V + H: one student, Visual: three) drew the FBD correctly. All other students drew the FBD incorrectly or did not provide an answer. During the first interaction using Configuration 1, only those students who received enhanced visual cues provided a correct FBD (V → V + H: 44.4%, and Visual: 63.6%). On the other hand, all participants who received minimal visual cues and haptic feedback for Configuration 1 (H → V + H treatment) drew the FBD incorrectly; ten participants drew the arrow of the forces acting on the joints in the same direction of the arrows from the forces acting on the members (Error 1). None of the participants drew the reactive forces acting on Joint A and Joint C (Error 2). For instance, participants ID3 and ID5 answered Question A (see Figure 6), indicating that member AB was in tension, BC under compression, and AC was a zero-force member. Participants incorrectly drew the forces aligned with the member AB in an outward direction and the forces aligned with the member CB in an inward direction. Figure 7a,c illustrate Error 1. Moreover, participant ID3, in its first interaction (see Figure 7a), did not include the reactive forces, illustrating Error 2.

During the second interaction, the enhanced visual cues were activated, and we asked participants to revise their drawings. Although all FBD diagrams provided during the first interaction were incorrect, eight participants considered that the first interaction's drawing was correct and made no changes. Three participants did changes: one participant added the reaction forces correctly, and two participants added the reaction forces incorrectly (e.g., at least one force was drawn in the wrong direction). The three participants that added reaction force maintained the wrong direction of the other forces (e.g., forces counteracting the members' forces).

TABLE 6 Pretest and posttest scores comparison

		Pretest (%)		Posttest (%)			Paired *t*-test			
Treatment	*N*	Mean	*SD*	Mean	*SD*	Δ	DF	*t*-value	*p* value	Effect size
H → V + H	11	68.67	20.33	96.00	7.44	27.33	10	−5.76	<0.001	1.74
V → V + H	18	60.44	15.33	87.67	10.00	27.22	17	−6.9	<0.001	1.62
V	22	55.00	23.33	89.89	17.11	34.89	21	−6.41	<0.001	1.37

TABLE 7 Classification of students' FBD

					Experimentation (%)								
		Pretest (%)			First interaction		Second interaction			Posttest (%)			
Treat-ment	**N**	**C**	**I**	**NA**	**C**	**I**	**C**	**I**	**NA**	**C**	**I**	**NA**	
H → V + H	11	9.1	72.7	18.2	0.0	90.9	0.0	90.9	9.1	0.00	100.0	0.0	
V → V + H	18	0.0	83.3	16.7	44.4	50.0	44.4	50.0	5.6	16.7	83.33	0.0	
V	22	13.6	59.1	27.3	63.6	31.8	No interaction		4.5	9.1	77.27	13.6	

Abbreviations: C, correct; I, incorrect; NA, no answer.

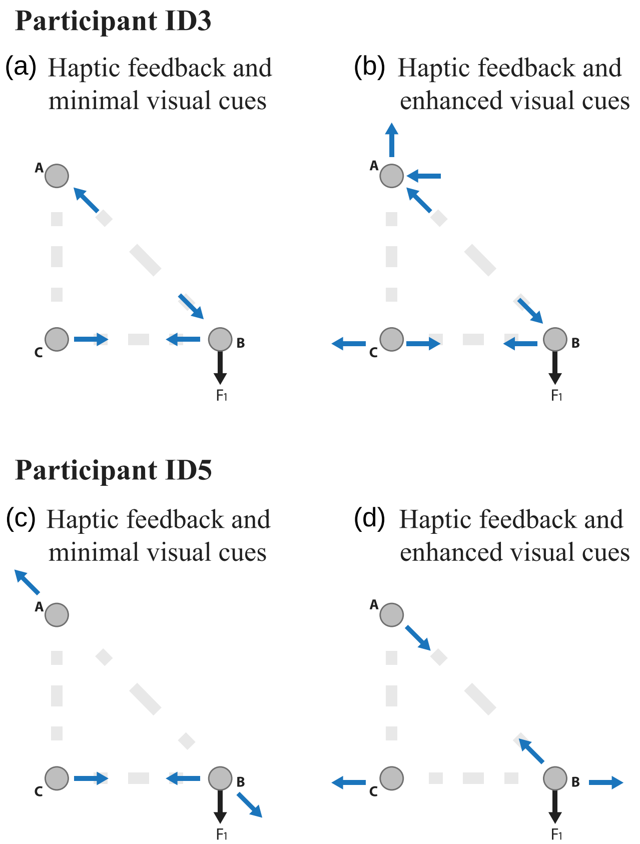

FIGURE 7 Examples of incorrect free body diagrams, Error 1 (A, C), and Error 2 (A, C, and D)

For instance, Participant ID3 incorrectly added the reaction force in Joint C (see Figure 7b) and maintained the wrong direction of the other forces. Only Participant ID5 changed the forces' direction counteracting the members' force (see Figure 7d) but did not include the reaction forces. Participant ID3 wrote that enhanced visual cues provided information about the reaction forces and forces. Participant ID5 wrote that enhanced visual cues provided information about the change in the direction of the forces. Results suggest that participants were unable to analyze all of the information provided by the enhanced visual cues, and the majority of students never activated the visualization of the FBD.

Results from V → V + H and Visual treatments support the hypothesis that learners were unable to analyze all the information provided by the enhanced visual cues. Enhanced visual cues display the FBD of each of the three joints in Configuration 1. Some of the students, 50% from the V → V + H treatment and 31.8% from the Visual treatment, failed to replicate the information displayed by the computer screen in their worksheets.

Table 8 shows the classification of incorrect representations in Error 1 (students incorrectly drawing the joints' forces), Error 2 (students problems drawing the reactive forces of Joint A and Joint C), and answers that have Error 1 and Error 2.

Table 8 shows that in all of the phases of the study, the majority of students had both Error 1 and Error 2 in

TABLE 8 Distribution of errors in the representational answers

		Percentage of errors in each phase of the study									
					Experimentation						
		Pretest			First interaction		Second interaction		Posttest		
Treatment	***N***	**E1**	**E2**	**E1 + E2**	**E1**	**E1 + E2**	**E1**	**E1 + E2**	**E1**	**E2**	**E1 + E2**
H → V + H	11	9.1	0.0	63.6	9.1	90.9	9.1	90.9	18.2	0.0	81.8
V → V + H	18	0.0	0.0	83.3	38.9	11.1	38.9	11.1	5.6	0.0	77.8
V	22	4.5	9.1	45.5	9.1	22.7	No interaction		0.0	45.5	31.8

Abbreviations: E1, Error 1; E2, Error 2; E1 + E2, Error 1 and Error 2.

their FBD. Error 1 occurred when students indicated the same direction of the forces acting on the members and the joints. Error 2 occurred when students did not include or failed to indicate the reactive forces' right direction (see Figure 7).

Error 1 alone was more common than Error 2, except for the posttest results in the Visual treatment, which showed that 45.5% of the students had Error 2 alone. Error 2 alone was not found in the experimentation phase. During the experimentation phase, results suggest that enhanced visual cues helped students correctly draw the reaction forces. For instance, in the $V \rightarrow V + H$ treatment, Error 1 and Error 2 was reduced by 72.2% from the pretest to the experimentation phase. In the V treatment, Error 1 and Error 2 was decreased by 22.7% from the pretest to the experimentation phase. Students in the $H \rightarrow V + H$ treatment mainly had Error 1 + Error 2 (90.9%). A possible explanation for this result is that enhanced visual cues showed the reaction force's direction and magnitude. The haptic feedback relied on the students' analysis of the reaction forces based on the members' forces.

Finally, the posttest results suggest differences between the sequenced approach of $V \rightarrow V + H$ and the Visual treatment. Students in the sequenced approach had mainly a combination of Error 1 and Error 2, while students in the Visual treatment had mainly Error 2 alone.

4 | DISCUSSION AND IMPLICATIONS

This study aimed to demonstrate the process of designing a visuohaptic learning activity following a learner-centered design approach. We hypothesized that using a LCD to design the visuohaptic simulation combined with a scaffolded learning approach would help students increase their conceptual understanding of forces and their representational skills (e.g., drawing FBD). Based on our *t*-test results of pre-and post-test scores, we accepted the hypothesis for the conceptual questions. Our first finding indicated a statistically significant learning gain between pretest to posttest in all three conditions ($H \rightarrow V + H$, $V \rightarrow V + H$, and Visual), and the large effect size suggests a strong correlation between all three combinations of the implementation and students' learning. However, the learning gain difference between the three treatment groups was not significant. These findings are aligned with Yuksel and colleagues' [58] study, which suggested no statistically significant learning differences between sequenced approaches. Furthermore, the present study showed no statistically significant learning differences between students who interacted with the visuohaptic simulation with only enhanced visual cues and the students who interacted with the visuohaptic simulation in a sequenced approach.

Pretest results were used as the baseline of student's knowledge and yielded no significant differences among all treatment pretest scores. Pretest results suggest that students mostly struggled to determine support reactions of a horizontal truss member when a force acting on positive *x*-direction (Structure 1, Configuration 2). All groups corrected their answers after the first interaction; however, all students in the $H \rightarrow V + H$ group corrected their answers after the second interaction, when haptic feedback was supported with enhanced visual cues. Students in the $V \rightarrow V + H$ group, on the other hand, were able to correctly answer support reaction in Configuration 2 after engaging with enhanced visual cues. However, after adding haptic feedback, the number of incorrect answers increased again. Since this observation only happened in Configuration 2, it is not possible to discuss the sequencing effect on students' understanding of this matter. Similarly, Yuksel and colleagues [58] also showed that $V \rightarrow V + H$ groups' students increased their incorrect answers in the posttest's procedural questions. Therefore, these results may suggest that the sequencing effect may change by the type of questions.

Further analysis showed that haptic feedback facilitated students to correctly interpret the members in tension or compression from the truss structure. However, results also suggested that identifying the zero-force members on Structure 1 was challenging for students who received haptic feedback and minimal visual cues ($H \rightarrow V + H$ treatment). Moreover, participants in the $V \rightarrow V + H$ treatment were able to identify the zero-force members from the enhanced visual feedback, but they did not show an improvement after the second interaction (adding haptic feedback). Mejia et al. [28] found a similar result when examining their participants' understanding of a truss system's internal forces via physical manipulatives. This result may suggest that it is difficult for students to identify a zero-force member on a truss structure through the sense of touch. For instance, in our visuohaptic simulation, students might think that the haptic feedback did not move due to the simulation's failure. Further investigation is needed to determine why students were unable to identify a zero-force member on a truss structure through the sense of touch.

Regarding the representational knowledge (e.g., FBD), students' pretest responses indicated that they had considerable difficulty correctly drawing all of the forces acting on a joint. While FBD have been found to have a positive impact on solving a problem [8,39], research has shown that students and even physics experts struggle to draw a correct FBD of complex structures [36,48,61]. Therefore, it is important to support students' understanding of how to draw an accurate FBD by including every acting force on objects. In this study, students in all three conditions failed to correct their incorrect FBD's from pretest to posttest. Students who drew correct FBDs in the H → V + H group changed their FBDs after the first interaction (only haptic feedback was on) and failed to draw reaction forces on the joints, presented explicitly by the enhanced visual cues (e.g., see Figure 3). As shown in Table 8, the H → V + H group increased the number of E1 + E2 after the first interaction and did not change after the second interaction. Particularly, these students mostly failed to recognize the mutual nature of forces (equal and opposite directions), as Steif [47] addressed in his seminal work. On the other hand, students in the V → V + H group increased their correct FBD representations during the first interaction (only enhanced visual cues) and kept the number of correct representations the same after the second interaction (see Table 7). However, these students provided more incorrect representations of FBDs in the posttest. Similarly, the visual treatment dropped the percentage of correct answers from the experimentation phase to the posttest. Hence, students' answers were based on the conceptual and representational information learned during the interaction with the visuohaptic simulations. Enhanced visual cues, which displays the FBD, did not promote reasoning among the participants regarding the forces that act on the joints. This could explain the decrement of correct responses from the participants once they were done using the visuohaptic simulation.

Moreover, incorrect answers were provided during the interaction phases. This finding suggested that despite providing students FBD with colored arrows when they turned on the enhanced visual cues, students were not able to make meaning of the diagrams in a way that they could recreate the diagrams on their worksheets. We believe that students focused their attention on the joint members and reacting forces rather than paying attention to identifying which forces acted on the relevant joints.

Moreover, we hypothesized that the failure of the enhanced visual cues in the H → V + H participants could be caused by the amount of information provided visually or the disassociation between the way learners interact with the structure and the FBD. Enhanced visual cues showed all the forces acting on the structure, differentiated by color, size, thickness, magnitude, and positions. By rolling over the joints, information about the forces acting on the joints were provided. Learners used the haptic device to interact with the structure and switch to the mouse to visualize the FBD, causing an unnatural interaction. Additionally, the experience failed in guiding students in the analysis of the forces acting on the joints. The forces on the joints acted in the opposite direction to the forces acting on the members. The majority of participants indicated that the forces acting on the joints had the same direction as the forces acting on the member. Here, we can argue that the visuohaptic simulation facilitated the exploration as a conceptual component of reacting forces, but the guidance of the worksheet and the nature of the assessment, as well as the unnatural interaction, did not support students' representational development, resulting in increments of incorrect FBDs (see Table 8).

On the positive side, evidence in this study suggests that visuohaptic simulations implemented in a sequenced approach can offer students a vehicle to conceptualize abstract concepts, such as tension, compression, and zero force. H → V + H group successfully connected the haptic feedback they received when they held each truss member with the experienced forces. When students in both treatment groups experienced one type of modality (visual or haptic) first and then added the second modality, they learned the force-related concepts better [23,58]. Additionally, the haptic feedback provided students with a new dimension for conceptualizing forces. This finding could be related to embodied cognition theorists' arguments about how perceptual and physical experiences affect an individual's understanding of a concept [17,56].

Previous work that has used visual cues and haptic feedback to represent abstract concepts in science has shown mixed results in terms of their effect on students' conceptual learning [59]. While Wiebe et al. [55], Park et al. [35], and Sanchez et al. [41] found that the combination of visual and haptic feedback did not provide an advantage over the visual modality, Magana et al. [23] determined that adding haptic feedback in a sequenced manner increased students' performance. Therefore, we used a visuohaptic simulation following a sequenced approach and visual-only to identify students' improvements of conceptual learning and representational skills of FBDs for truss systems. Our findings suggest that: (a) the design of visuohaptic simulations and the assessment worksheet for learning purposes is a complex process [53], (b) design of the experiment was a deliberate process, and the experiment was still very hard to execute, and (c) facilitating students understanding and application of FBD is not a straightforward process. Furthermore, the use of multiple ways of providing visual information may overwhelm students [5].

4.1 | Implications and limitations for teaching and learning

Implications of our study relate to the design of learning environments that follow a LCD. Our study first focused on requirements analysis and specification and identified the learners' needs, prior knowledge, and research that informed our intervention's design. As part of the second level, we consulted the literature and deliberately implemented six multimedia learning principles to design the visuohaptic simulations and the guiding worksheet. Specifically, guidance from White and Gunstone's [54] pedagogical approach helped students through the experimentation and observation phases. In the third level, we systematically investigated the effectiveness of our approach. Results, in general, suggested that structural analysis is a complex topic for learning and teaching. For instance, although our learning activity complemented the lecture, we found conceptual and representational problems in students' answers at various study stages. The complexity of the topic can explain incorrect answers (e.g., it requires analyzing the forces of various components and joints). Moreover, incorrect answers were found in the posttest (e.g., after the lecture and the learning activity), which suggested that learners require multiple interventions to acquire conceptual and representational knowledge.

Regarding our learning activity, positive results were primarily identified in terms of conceptual learning (e.g., significant learning gains and increment of intuition). Enhanced visual information and haptic feedback helped students identify the direction of the truss members' forces (see Tables 4-6). This study did not investigate the perception of the force magnitude in the members of the truss structure. Future investigation may include a perceptual question about identifying the magnitude of the forces acting on the structure. Investigating the perception of forces in trusses may contribute in identifying affordances and challenges of visuohaptic simulations for learning.

Promising results were found in conceptual learning (e.g., significant learning gains and strong effect sizes). Nonpromising results in students' representational competencies (e.g., drawing FBD) left us with more questions and leads for further inquiries.

Multimodal learning offers principles for designing interventions that can provide information from multiple sources in a complementary way [33]. In this study, we intended to develop and examine a multimodal learning environment supported by visual and haptic feedback to optimize a complex statics concept's learning gain. Previous work has shown that students can benefit from the different representations of phenomena and learning media [16,27]. Thus, this study's implications regarding teaching and learning revolve around the idea of how to achieve knowledge transfer and help students revise nonnormative conceptions about the forces in a truss system. The learning materials used in the experimentation phase showed some promise toward this goal. However, the learning experience could have better supported and guided students understanding and application of all concepts involved in the intervention. Results from the study suggested that the experimentation worksheet requires more scaffolding to highlight important concepts and help students build understanding by recalling prior knowledge, forming intuitions about the phenomena, and testing their understanding with the simulation.

Although that was our initial goal, perhaps students could not make the connection between the force feedback and their conceptual analog, and therefore did not benefit from the rest of the learning experience. It is also possible that students may have been distracted by other elements of the simulation. A possible remedy for this issue is to embed the instructional overlay of the worksheet within the simulation environment and provide some intelligent feedback to check students' understanding at intermediate points to make sure students are benefitting from the learning experience. Another way to promote comprehension of the forces acting in the joint is by displaying all three FBDs of the joints of the same configuration concurrently, for instance, by providing a screen where learners can simultaneously observe all FBDs of a configuration and also providing guidance in observing all key elements in the configuration.

The assessment utilized for this study included closeended questions, such as multiple-choice, right or wrong responses, or fill in the blanks, and free responses such as drawing FBDs for specific joints. The power of this study is low due to the small number of participants. To reduce the impact of the low power in the study's findings, we examined the experimentation answers and categorized the errors made by learners in the FBD. Future research focused on conceptual understanding, and representational competencies of the structure analysis should include a higher number of participants to expand these research findings.

Moreover, quantitative methods of inquiry provide a robust statistical analysis with gains, means, and mathematical comparisons but do not provide an in-depth analysis of the knowledge and nonnormative conceptions students have before, during and after the intervention. Open-ended questions would have offered more information about students' conceptual understanding and terminology used to define the forces they experienced. Since closed-ended questions do not allow students to expand their ideas, which may provide new insight into the analysis, we suggest including some open-ended sections to the pretest, posttest, and experimental sheets for future studies. Another strategy would be to administer the pretest and posttests as a clinical interview to a random subset of participants to identify areas of conceptual difficulty, diagnose students' nonnormative conceptions, and generally understand how students make sense of the content based on the various treatments.

Regarding the experimental design, students in the Visual condition only interacted with the visuohaptic simulation once. Students in the sequenced approaches interacted twice with the visuohaptic simulation. Time on task and exposure to the learning content was higher on the sequenced treatment. We acknowledge the students' disadvantage in Visual treatment. However, this treatment allowed us to investigate the value of haptic feedback in virtual environments.

Finally, we proposed the design of more configurations of truss structures that allow learners to acquire a complete understanding of the effects of an applied force on a truss structure. Configurations might include more joints and truss members and changes in the applied force. Also, including in the worksheet questions that require learners to feel and observe the forces acting on the joints and the members may help build knowledge about the forces' distribution at the different components of the structure (e.g., action and reaction forces).

5 | CONCLUSIONS

We followed a LCD to designing a learning environment to support the conceptual understanding of a challenging statics concept via two essential sensory modalities (visual and haptic feedback) following a sequenced approach. Our evaluation suggests (a) the potential of visuohaptic simulations to offer a significant opportunity to learn abstract and difficult concepts in statics, such as the notion of tension and compression in truss members, and (b) challenges of using this same environment to improve diagraming FBD for each truss joints. Although students' active engagement with the learning materials and the observed learning gain between pretest and posttest indicated a promising future for the sequenced modality approach, there is still room for further improvement and research. Specifically, the results inform us about the affordances of sequencing between visual cues and haptic feedback and the effects of the order in which each modality was presented. One of the limitations found in this study was the small sample size used in each session group and the use of better assessments aligned with the instructional environment. Future work should involve research with larger sample size, a design that allows different sequenced configurations of both modalities, and qualitative analysis to investigate students' explanations and reasoning.

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CONFLICT OF INTERESTS

The authors declare that there is no conflict of interests.

ETHICAL APPROVAL

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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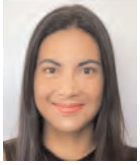

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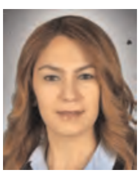

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APPENDIX A: . PRETEST

Last Name:	First Name:
Lab section attending:	

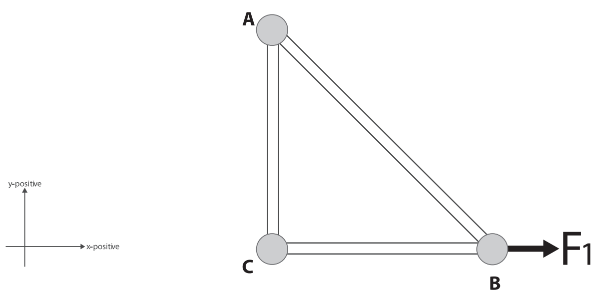
****INSTRUCTIONS****

The Truss below, Figure A1: Truss 1, represents a structure that could be used to support a sign on the outside of a building. Please answer the following questions related to this truss.

(a) Using Figure A1, please identify whether the truss members are in tension, compression, or are zero-force members, and indicate your choices on the table below. (You do not need to show any calculations.)

Truss member	Tension	Compression	Zero force member
AB	o	o	o
BC	o	o	o
AC	o	o	o

(b) Draw the FBD to show the forces acting on the **Joints A, B, and C** when F_1 is applied on the Joint B in y-negative direction



(c) How confident are you about your previous answer?

1. Very confident
2. Somewhat confident
3. Neutral
4. No very confident
5. Not at all confident

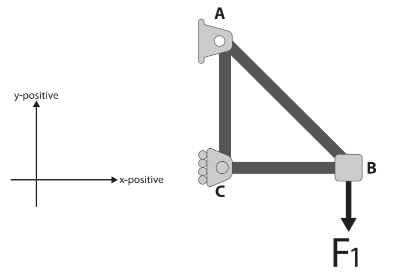


FIGURE A1 Truss 1

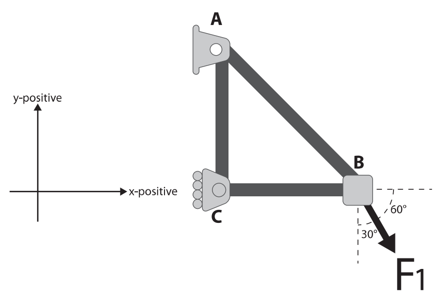
****INSTRUCTIONS****

In the next set of questions, F_1 (the original force), is applied on Joint C in the positive-x direction (see Figure A2).

(d) Using Figure A2, please identify whether the truss members are in tension, compression, or are zero-force members, and indicate your choices on the table below. (You do not need to show any calculations.)

Truss member	Tension	Compression	Zero force member
AB	o	o	o
BC	o	o	o
AC	o	o	o

(e) Draw the FBD to show the forces acting on the **Joints A, B, and C** when F_1 is applied on the Joint B in y-negative direction



(f) How confident are you about your previous answer?

1. Very confident
2. Somewhat confident
3. Neutral
4. No very confident

5. Not at all confident

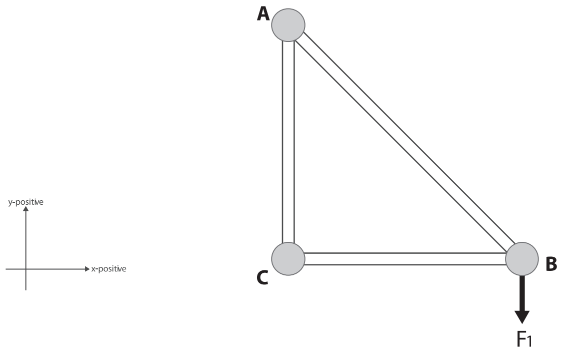


FIGURE A2 Truss 1

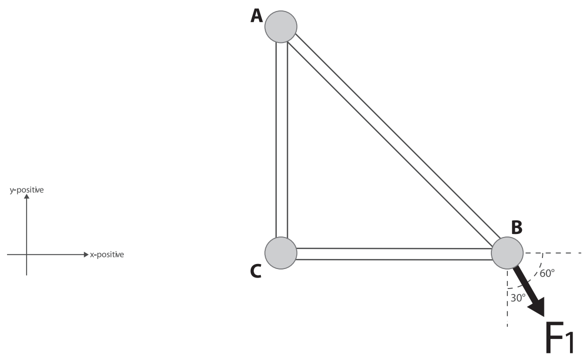
INSTRUCTIONS

In these questions, the force F_1 is applied on Joint B with an inclination of 60° below the horizontal, as shown in Figure A3.

(g) Using Figure A3, please identify whether the truss members are in tension, compression, or are zero-force members, and indicate your choices on the table below. (You do not need to show any calculations.)

Truss member	Tension	Compression	Zero force member
AB	o	o	o
BC	o	o	o
AC	o	o	o

(h) Draw the FBD to show the forces acting on the **Joints A, B, and C** when F_1 is applied on the Joint B in y-negative direction



(i) How confident are you about your previous answer?

1. Very confident
2. Somewhat confident
3. Neutral
4. No very confident
5. Not at all confident

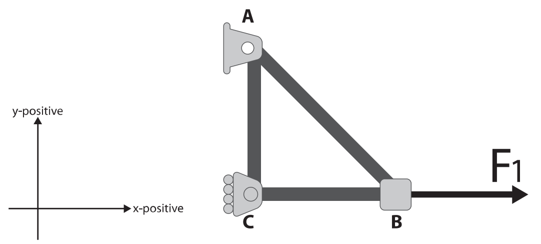


FIGURE A3 Truss 1