Tangible Digital Twins: Experiencing Structural Mechanics by Inducing the Sense of Stiffness via Hand Gestures in Virtual Reality

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Abstract

The behavior of structural elements governed by structural mechanics is often challenging to grasp in a theory-only classroom environment. This is due to the gap between abstract theoretical descriptions of structural behavior versus the experience and perception of the deformation. To bridge this gap and facilitate better comprehension of structural mechanics concepts, we develop a virtual reality (VR) application that allows users to interact with virtual objects in real time with their hands. Users can deform virtual entities using realistic hand gestures, and the sense of stiffness is evoked by using the deformation speed as a proxy for the object's resistance to deformation. To achieve this goal, our design requires the user to move their hands at a speed inversely proportional to the member stiffness, stopping deformation if this constraint is violated. To assess the effectiveness of these techniques, we introduce three game scenes within our study with beams under tension, compression, bending, and torsion. Preliminary results from an early pilot user study show the promise of the proposed platform in inducing a sense of stiffness. The proposed application provides a promising pathway for immersive experiential learning of engineering concepts that would otherwise require expensive laboratory experiments.

Introduction

Structural mechanics involves studying members' force and displacement distribution under different load conditions. These effects have complex dependencies with the geometry, shape, configuration, and material properties of the systems under study and the types, magnitudes, and mechanisms of the loads applied. Understanding and learning these relationships requires a strong combination of spatial imagination, physical perception, and structural mechanics laws. Traditional models for course delivery in structural mechanics rely on lectures describing these behaviors and the underlying structural mechanics concepts using classroom illustrations and demonstrations of members under loads in a structural laboratory. While conducting laboratory experiments is often considered an essential method for teaching structural mechanics theory [1], substantial investment is required to build and maintain labs, limiting its widespread application. Even if such resources exist, their rigidity and the one-time nature of these demonstrations hinder students from exploring scenarios beyond the standard setup. This limitation restricts students' ability to independently investigate and discover at their own pace. This sequential presentation of conceptual lectures in the classroom followed by experimental demonstrations (theory first, practice later) also results in a disconnect between theory and application and delayed reinforcement. Although various types of multimedia, such as images and videos, are often used as alternatives for explaining structural mechanics problems, their effectiveness is constrained by the lack of interactivity and immersiveness. Therefore, there is a need to develop cost-effective structural mechanics education methods that yield satisfactory learning outcomes.

The last decade has seen the rapid development of Virtual Reality (VR) technology. Besides its extensive popularity in entertainment, numerous studies have been conducted to explore the feasibility of applying VR technology to education across various fields, such as design [2], business [3], and physics [4]. In a comprehensive review [5], the authors summarized and categorized the application domains and learning contents of a considerable number of VR-based education studies, highlighting the wide range of application scenarios and the tremendous potential of VR in education. Utilizing VR for educational purposes offers multiple advantages. Firstly, the immersiveness provided by virtual environments enhances students' motivation, engagement, and concentration on the teaching material, as revealed by numerous studies [6,7,8]. Additionally, the application of VR provides virtual experiences regardless of the physical location and access to expensive facilities, promoting equality in education [9]. VR technology can create immersive and engaging learning environments that stimulate active participation and information retention [10]. This can be achieved through the use of VR for the gamification of challenging concepts [11].

Literature Review

Multiple studies have investigated the application of VR in various visualization tasks for civil engineering-related topics, including construction monitoring [12,13], building information modeling (BIM) [14,15], and structural inspections [16]. Some studies also focus on the application of VR in structural mechanics education. Alipour et al. [17] propose a framework for visualizing the FEM analysis results with mixed reality equipment. Zhang et al. [18] implemented a VR platform to visualize basic structural deformations. Hambli et al. [19] combine a neural network with VR to calculate and visualize the real-time response of structures to external loads. The studies above revealed the potential of utilizing VR for structural mechanics education.

Structural mechanics deals with understanding materials, structures, and as well as their behavior when they are acted upon by external forces. However, simple visualization in VR is incapable of producing such feedback and a sense of working with materials and structures. In recent years, haptic feedback technology has been applied for educational purposes [20,21], providing increased realism and immersive experience. However, the high cost of haptic equipment, limited access and adoption, and the need for pre-training to ensure proficient use restrict its practical application value. Pseudo-haptic feedback is a technique exploiting the dominance of visual perception in shaping the sense of object properties during visual-haptic interactions, which has been widely investigated and proved cost-effective [22,23,24]. It has been demonstrated that a virtual sense of force or weight can be produced by introducing a discrepancy between the user's action and the movement of objects in the VR environment [25,26]. For instance, Weser and Proffitt showed that when different speed limits are set for lifting objects with different weights, the lower speed limit will give users a sense of higher weight or larger resistance force [27]. These studies imply the feasibility of introducing the structural concepts by artificially setting different deformation speed limits for different specimens to simulate the sense of stiffness. However, most of these studies use handles, computer mice, or hand controllers for human input and interaction, which have limited simulation effects, constraining the immersiveness. With the development of computer vision and artificial intelligence, hand gesture detection and tracking has become a mature technology for various applications [28][29]. Gesture interaction provides a cost-effective way to control and manipulate virtual objects in VR environments [30]. With a camera capturing video of the hands and the built-in gesture recognition program, the gestures and movements of fingers and hands can be recorded as controlling input. Moreover, it allows users to interact with virtual objects in highly intuitive movements, significantly creating new possibilities for realistic, immersive, and intuitive experiences.

We propose to create virtual objects that deform in realistic ways and can be interacted with by the users by means of intuitive hand gestures. These virtual objects follow the rules of structural mechanics and respond to the forces considering their stiffness. These virtual objects can be paired with real test specimens in the laboratory to mimic real structural tests, thus enabling students and educators to replicate and revive laboratory experiments in the virtual environment. Therefore, this system constitutes a digital twin that can be controlled with the hands in the same ways a user handles and manipulates a real deformable object. This digital twin can then be enriched with educational information such as stress and strain distributions on the surface and inside the objects. The resulting simultaneous presentation of the structural mechanics concepts as the user works with the digital twin can be leveraged to bridge the theory-practice gap in structural mechanics education. This paper is part of an effort to study the feasibility of using immersive and tangible virtual reality tools to enhance engineering intuition in structural engineering education. The broad goal of this effort is to evaluate the extent to which virtual reality technologies can be utilized to provide students with the foundation for developing engineering intuition in structural engineering. Specifically, this preliminary study aims to evaluate the feasibility of inducing a sense of stiffness by combining deformation speed limits with hand tracking in a VR environment.

Proposed System

We create a VR tool that generates and visualizes a beam that can be deformed using the user's hands. We then create a method to correlate the speed of the deformations with the stiffness of the beam, thus inducing a sense of stiffness for the user. We finally evaluate the early feasibility and performance of the system through a pilot user study. The overall structure of the system consists of three layers: the user interface, the deformation module, and the stiffness module. A detailed representation of the overall system architecture is illustrated in Fig. 1. The proposed system first captures hand movements with the built-in camera on the VR headset, which serve as the input for the entire system. Subsequently, the server processes the data, calculates the deformation of the object, and outputs the visualized deformation in the VR headset.

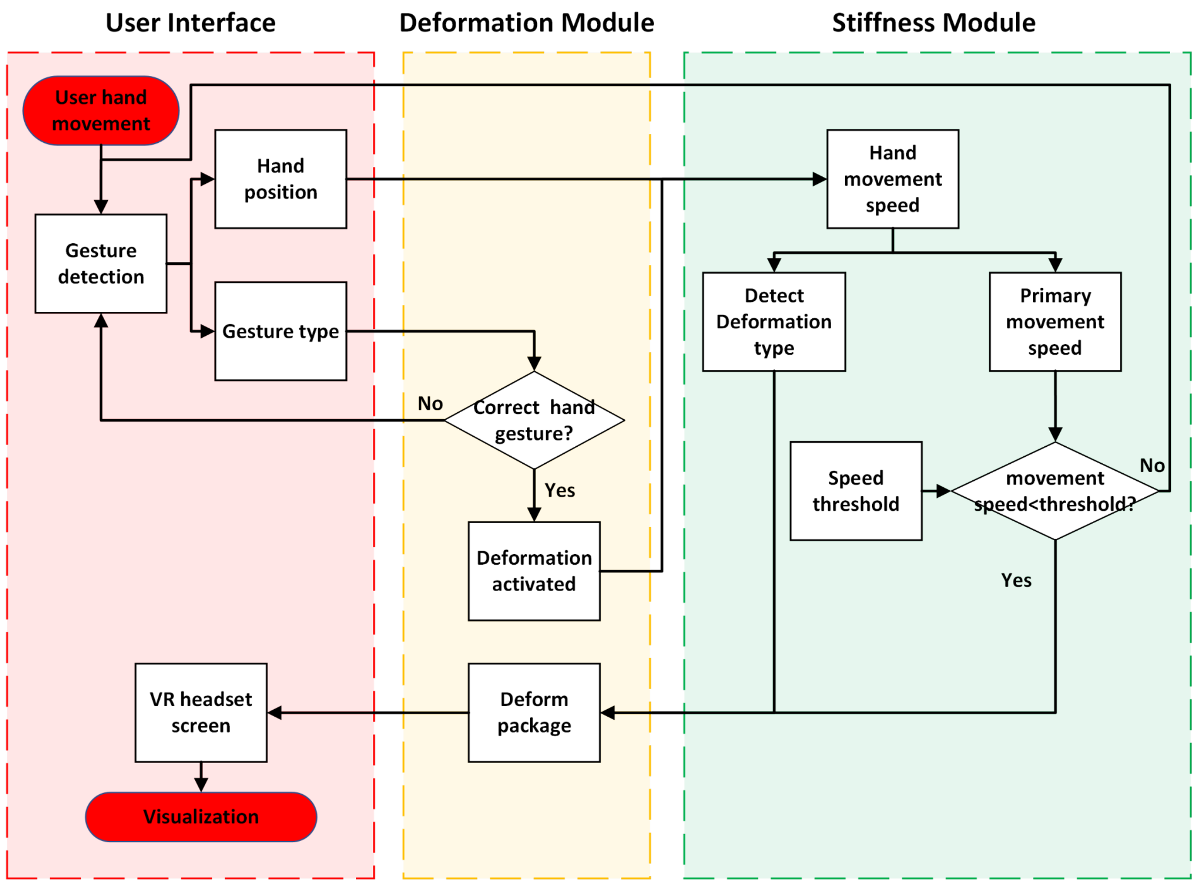

Fig. 1. Proposed System Architecture.

The user interface part facilitates user interaction with the virtual object. At the input end, a camera on the VR headset, coupled with the built-in hand tracking algorithm, records the movements and gestures of the user's hands. At the output end, the deformed object and virtual hand movements are displayed on the screen of the VR headset, providing feedback to the user.

The deformation module receives information from the user interface to determine the deformation status of the object. The gesture of the left hand, in which all five fingers pinch together, is first utilized to judge if the object is grasped. Upon successful grasping, the gesture of the right hand, where the thumb and index finger form a letter "U" shape, is detected to determine if the deformation mode is activated. The required gestures for grasping are shown in Fig. 2, enhancing the immersive experience by simulating the sense of grasping and manipulating the object. In this design, the two hands should point toward each other during the deformation, otherwise, the object is considered released, which is consistent with the user experience with real objects.

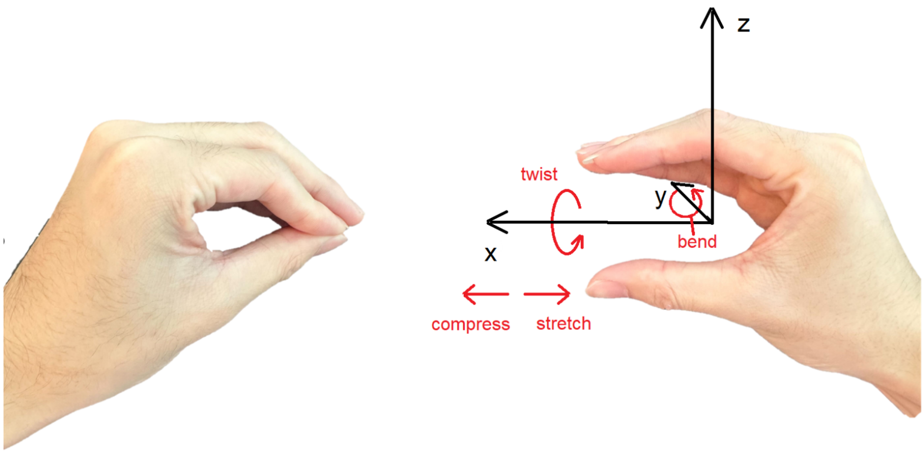

Fig. 2. Definition of the hand gestures used in the deformation module.

Once the deformation mode is activated, the object's color changes, providing feedback to the user to indicate that the object is ready for deformation. The relative hand movement direction and speed are then calculated by real-time detection of the hands at a frequency of 50 Hz, which is subsequently utilized by the stiffness module to determine if the movement can trigger deformation and identify the type of deformation. In this early application, four deformation types, including stretching, compressing, bending, and twisting, are created. The right hand movement is decomposed into movements along and rotations around the three axes relative to the left hand. The primary movement is then determined by comparing the ratio of movement components in different directions, subsequently triggering the corresponding deformation type for visualization. Specifically, movement of the right hand along the positive x-axis (see Fig. 2) corresponds to compressing, while movement along the negative x-axis corresponds to stretching. Rotation about the x-axis results in twisting, and rotation about the y-axis leads to bending. The rendering of the resulting deformations is presented in Fig. 3.

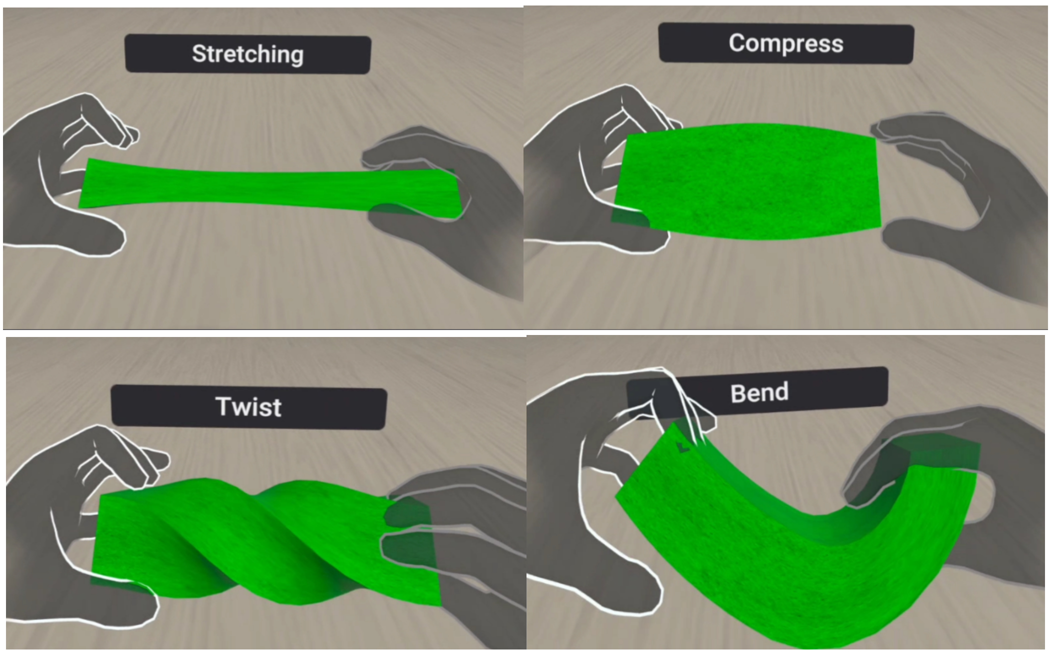

Fig. 3. Rendering of the deformation modes created in this study.

The stiffness module encompasses the underlying logic relating the object's response to input movement to its stiffness. As mentioned in the deformation module, hand movement direction and speed are key inputs for the stiffness mechanism. The speed of the movement component is compared to a threshold, which is inversely related to stiffness. If the speed exceeds this threshold, deformation becomes locked, and a 'hand movement too fast' reminder is displayed to inform the user that their force cannot deform the object (Fig. 4). In other words, deformation can only occur with slow movements for stiff objects. This is consistent with intuition as the user expects to encounter higher resistance to deformation from a stiffer object.

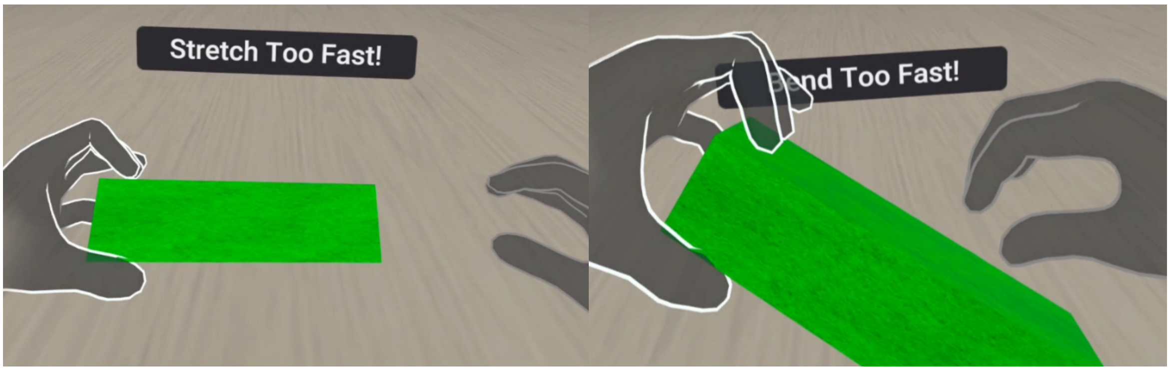

Fig. 4. The stiffness mechanism deactivating deformation if the threshold is exceeded.

System Implementation

The user interface was implemented using the Meta Quest 3 VR headset, which is equipped with a camera designed for capturing hand gestures and movements. The virtual environment is developed with the C# programming language based on the Unity game engine [31]. The built-in hand interaction software development kit (SDK) was applied for hand tracking. We also render the virtual hand symbols in the VR environment, enabling users to perceive their own hands within the virtual space. In the deformation module, the Deform Package [32] plays a crucial role in generating a visible deformed object with the deformation data. The package creates a mesh for the object and takes the external load as input, subsequently calculating the displacement of each node while ensuring the structural deformation equations are satisfied. Three modes of deformations are enabled by the application which are, stretch-compress mode, bending mode, and twisting mode. The mechanisms of the three modes are described below.

The system enables the 'stretch-compress' mode of deformation through a class called BulgeDeformer. It calculates the direction along the bulge axis and determines the center and global position for visualizing the stretching effect. The center is computed as the midpoint along the forward axis of the bulge, and the global position is then calculated by extending from the center in the direction of the bulge axis, modified by the bulge factor along its axis. An interactive slider is used, which allows users to modify the object's shape, with changes dynamically updating the bulge factor. This factor, representing the degree of stretching or compressing, is recorded and applied, ensuring a responsive and immersive stretching experience in the virtual environment.

In visualizing and handling the bending operation, the rotation, scale, and position of the user's hand based on the object properties, such as its axis, angle, and top/bottom values, are calculated. When changes are detected, the code records the modification, updating the object's angle property and ensuring a dynamic and responsive bending experience for the object in a 3D environment. For visualizing and handling the twisting operation, a subroutine sets up angle gestures that represent the start and end angles of the twist. Users can interactively adjust these angles through their hands, affecting the twisting deformation of the associated object. Any changes to the start or end angles are recorded, allowing for dynamic and responsive twisting of the object in the virtual space.

Game design

To evaluate the proposed system, we create three interactive games. These games are then played by users and their experiences and feedback are recorded by using post-game surveys. The effectiveness of the proposed technique to induce the sense of stiffness is also evaluated by recording the performance of the users in comparing objects of different stiffness. To prepare the users for the games, a pre-game tutorial was also created (see Fig 5). The tutorial aims to provide the user with step-by-step training on the operation of grabbing and deforming the object. The tutorial has text, pictures, and video instructions, and the users are allowed to practice repeatedly with enough time in the tutorial to become familiar with controlling the virtual object with their hands.

Three games are then presented to the users to investigate the effectiveness of the proposed technique in conveying the sense of stiffness, as shown in Fig. 5. In each game, three repeated experiments are conducted, and two objects are generated for each experiment. In each pair, the size of the rectangular cross-section, material texture (e.g., steel, concrete, wood), and cross-section shape are varied for the three games, respectively. For each experiment, the deformation speed threshold of each object is randomly selected to be 0.25, 1, or 4 to simulate different stiffness levels. The users are asked to interact with the two objects and decide which one has a higher stiffness. In these games, the stiffness is independent of the factors (size, texture, and shape), to investigate whether the user can choose the stiffer object even if the visual appearance of the object contradicts that perception.

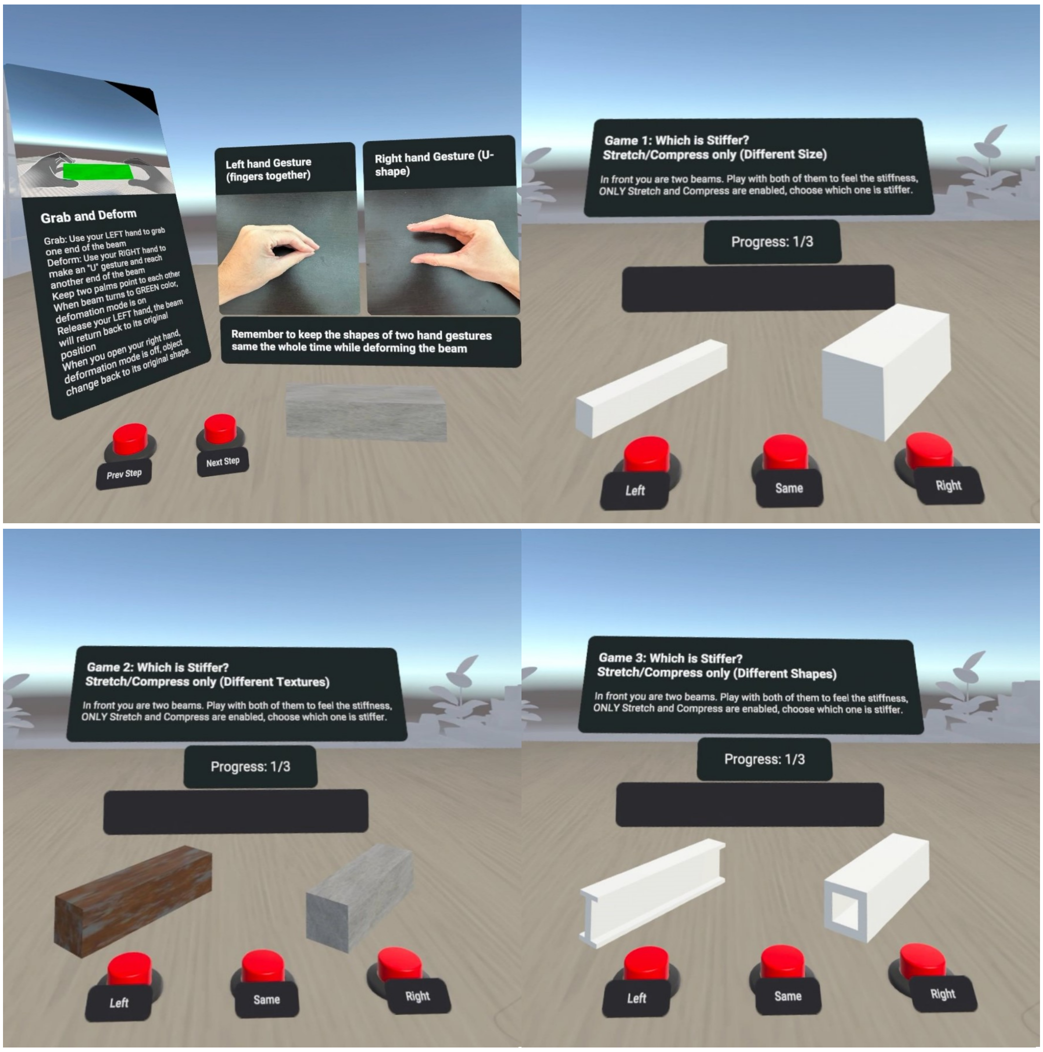

Fig. 5. Pre-game tutorial and games 1-3.

Pilot User Study

The pilot user study was performed with a small group of six participants who volunteered to participate in the study. First, the objective and procedures of the study were explained to the participant, after which a signed consent form was received from the participant. Then, a VR headset was provided to the participant, ensuring its comfortable adjustment and clear display (see Fig. 6). Next, the participant was asked to perform the pre-game tutorial to ensure comfort with the VR headset and its operation, including handling and deforming virtual objects in an immersive environment. Once the participant was comfortable with the VR headset, the experimental session was initiated. In this session, the participant was asked to play the three games explained in the previous section. The games in the experimental session involved using hand gestures to work with and deform virtual objects in a virtual environment. The participant was asked to evaluate and compare the feeling of the virtual objects with a variety of object pairs having different shapes, textures, and sizes. Each game was explained before the participant began, and instructions on how to perform the tasks were provided. The participant was encouraged to complete these games as accurately and quickly as possible. After completing all the games, the participant was asked to fill out a questionnaire to provide general feedback on the experience of working with the application and any issues encountered.

(a) A user playing a game (b) VR headset

Fig. 6. User study setup.

User experience survey. Aside form the general experience questionnaire, three standard questionnaires for the users of the VR application were prepared based on the System Usability Scale (SUS), Technology Acceptance Model (TAM), and the NASA Task Load Index (TLX). The System Usability Scale (SUS) [32], is a low-cost and reliable means to assess the perceived usability of a technology system. It consists of ten statements formulated alternatively in positive and negative forms, where the participant provides a subjective evaluation of the system's usability by giving a score of 1-5 (Table 1). Based on the scores of each statement, a final score between 0-100 is calculated for each participant. The Technology Acceptance Model (TAM) [34], was used to assess various factors that affect the acceptability of the VR application, including the interface style, perceived enjoyment, perceived usefulness, attitude toward using, and intention to use [35]. The NASA TLX method [36] evaluates the workload to use the VR application on a 7-point scale where 1 indicates very low and 7 indicates very high.

Table 1. Statements of System Usability Scale (SUS) evaluation

Statements	Evaluation scale
1. I think I would like to use this system frequently. 2. I found the system unnecessarily complex. 3. I thought the system was easy to use. 4. I think that I would need the support of a technical person to be able to use this system. 5. I found the various functions in this system were well integrated. 6. I thought there was too much inconsistency in this system. 7. I would imagine that most people would learn to use this system very quickly. 8. I found the system very cumbersome to use. 9. I felt very confident using the system. 10. I needed to learn a lot of things before I could get going with this system.	Strongly Disagree … Strongly Agree 1 2 3 4 5

Results and Discussion

a. Participants and general experience:

The participants of the user study were between 20 and 29 years old; two were female, and the remaining four were male. Five participants were from civil engineering backgrounds, and one was from economics. The general experience of the participants in the study is shown in Figure 7. Most participants had less to no experience in using VR previously. Regarding comfort with putting on the headset and the effectiveness of the application in conveying the sense of stiffness, the users' mean ratings were above average (3.5 out of 5). However, users' mean rating about comfort with playing the games and finding the deformation realistic was about 3 out of 5.

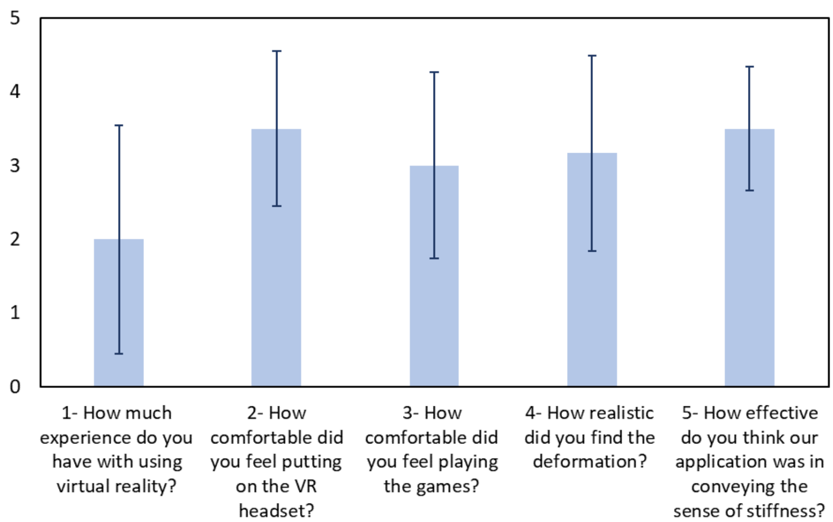

Fig. 7. General experience of users.

b. Results of games played by users

The rates of correct response in the games played by the participants are shown in Figure 8. It was found that when the success rate increases with an increase in the stiffness difference. Notably, when there was a significant disparity in stiffness levels, participants demonstrated the ability to accurately identify samples even when confronted with potentially misleading visual attributes such as size, texture, and cross-sectional shape. However, when the difference in stiffness was minimal, visual cues such as changes in cross-section and size tended to mislead participants, except in cases of medium stiffness differences. Interestingly, the evidence indicates that texture as a visual cue appeared to be less influential in misleading participants compared to size and cross-sectional shape. Overall, these initial findings align well with intuitions, suggesting a promising framework for the intended study. Nonetheless, to draw more definitive conclusions, further rigorous statistical analysis is warranted, which will be the focus of future investigations.

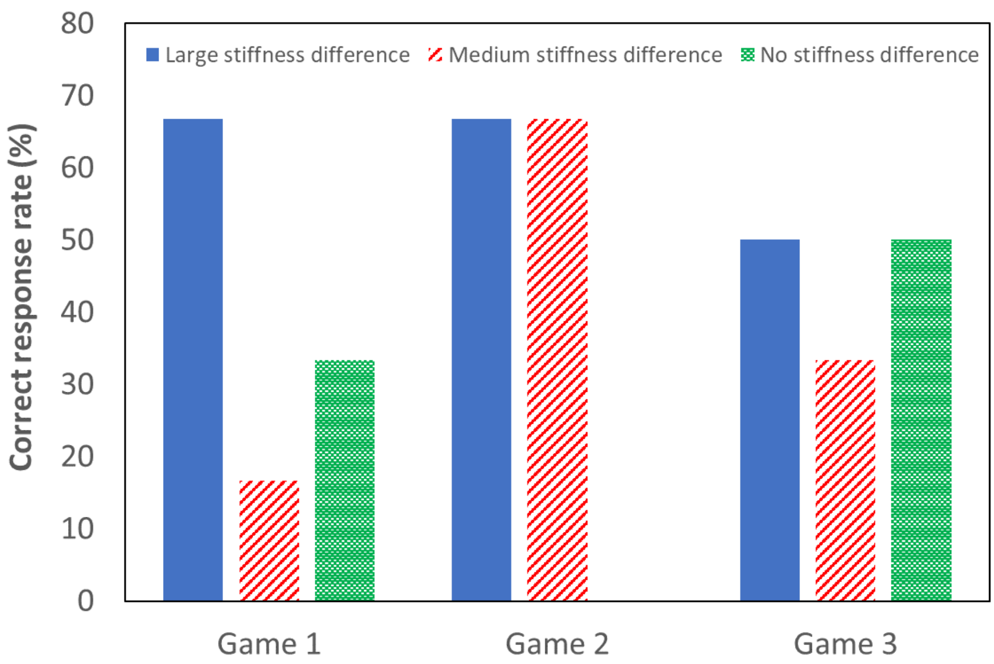

Fig. 8. Rate of correct responses by users in VR games.

c. System usability scale (SUS):

The SU values from the SUS model are shown in Table 2. As per [36], a System Usability Scale (SUS) score > 51 is deemed "OK" with relatively low acceptability margins, a SUS score >72 is regarded as acceptable with usability levels labeled as "good," and a SUS score surpassing 85 aligns with usability levels denoted as "excellent" [38]. Hence based on the average SUS scores for all users, the application at this preliminary stage can be deemed ‘OK’. Two out of six users, however, have SUS scores > 72, indicating ‘good’ usability levels.

Table 2: SU values for participants from System Usability Scale (SUS) model

Users	1	2	3	4	5	6	Average	Standard deviation
SU value	67.5	85	65	72.5	52.5	62.5	**67.5**	**10.84**

d. Technology acceptance model (TAM):

For the statements of TAM, the average scores ranged from 2.83-4.83, and the standard deviation ranged from 0.41-1.38 (Table 3). However, the average of all the statements is 4.17 on a scale of 5. Hence, the overall acceptance of the proposed VR application can be deemed satisfactory at this stage.

Table 3: Statements in the questionnaire for TAM model and corresponding results

Statements in the questionnaire	**Average**	**StD**
● Interface Style (IS)		
Deforming virtual objects using the VR app is easy.	3.50	1.38
Using virtual reality for learning deformation is a good idea.	4.17	0.75
I could easily control the deformation of the objects using the VR app.	2.83	1.33
● Perceived usefulness (PU)		
The use of such a VR application improves learning in the classroom.	4.67	0.52
Using VR during lessons would facilitate understanding of certain concepts.	4.83	0.41
I believe that the VR application is helpful when learning.	4.67	0.52
● Perceived ease of use (PEOU)		
I think the VR system is easy to use.	3.67	1.03
Learning to use the system is not a problem.	4.33	0.52
Operation with the system is clear and understandable.	4.33	0.52
● Perceived enjoyment (PE)		
I think the system allows learning by playing.	4.50	0.55
I enjoyed using the system.	4.17	0.75
Learning with such a system is entertaining.	4.50	0.55
● Attitude toward using (ATU)		
The use of such a system makes learning more interesting.	4.67	0.52
Learning through the system was boring.	1.67	0.52
I believe that using such a system in the classroom is a good idea.	4.67	0.52
● Intention to use (ITU)		
I would like to use the system in the future if I had the opportunity.	4.50	0.55
Using such a system would allow me to perform deformation experiments on my own.	3.83	1.17
I would like to use the system to learn structural mechanics and other subjects.	3.83	0.98

e. NASA task load index (TLX):

For the NASA TLX evaluation, the mean and standard deviation for each factor are shown in Figure 9. The factors are arranged in the order of mental demand, physical demand, temporal demand, performance, effort, and frustration level. Higher scores on a scale of 1-7 indicate a higher workload and vice versa. The mean values of each factor indicate that the perceived task load was medium to low. However, the standard deviation of the results for the two factors is greater than 3. The variation can be decreased by increasing the number of participants in future studies.

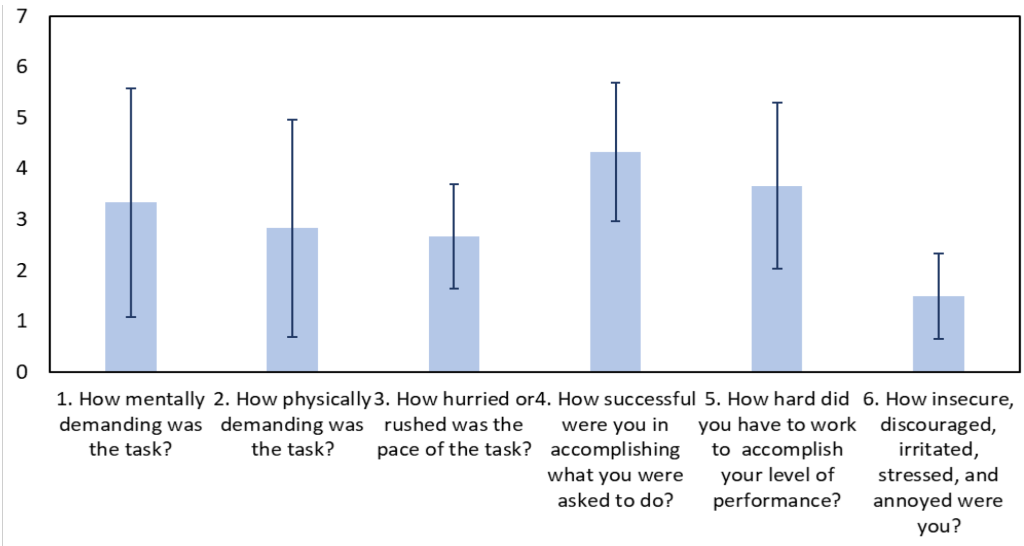

Fig. 9. Results of NASA Task Load Index (TLX)

Conclusions

A virtual reality (VR) application was proposed in this study that utilizes realistic hand gestures and speed-controlled deformation to enhance the comprehension of structural mechanics concepts by inducing the sense of stiffness. The system architecture of the proposed framework comprises three integral components: the user interface (UI) for intuitive interaction with digital twins, a deformation module utilizing customized hand gestures for realistic manipulation, and a stiffness module activated during deformation to simulate the resistance of structural elements. User choices are stored for analysis, and the UI includes pre-game training to enhance user understanding. The deformation module utilizes specific hand gestures and calculates hand movements to deform the virtual beam object in various modes that include stretching, compressing, bending, and twisting. The stiffness module uses a hand movement speed threshold, based on which the deformation of the virtual object is allowed or disallowed, to produce a realistic sense of stiffness.

To assess the effectiveness and acceptability of the VR application, the developed games were employed in a limited pilot user study. The results of the games depicted that users achieved higher success in identifying objects with higher stiffness when the stiffness differences between objects were sufficiently high. This aligns with expected intuition, indicating a promising system design. User experience survey feedback was also received from the participants and evaluated based on established frameworks such as the System Usability Scale (SUS), Technology Acceptance Model (TAM), and NASA Task Load Index (TLX). The SUS scores indicated an overall acceptable usability level. The TAM statements received favorable average scores, suggesting satisfactory acceptance of the VR application. The workload of using the application was also experienced to be medium to low based on the NASA TLX average scores. The results and evaluations of the user experiences demonstrated that the proposed VR application offers a promising platform for an immersive learning experience for users interacting with structural mechanics concepts.

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