Master of Science in Engineering

Virtual Reality Training Model for Post-Tensioning Construction: Framework and Application

August 2023

Department of Architecture & Architectural Engineering
The Graduate School
Seoul National University

Inwon Kim

Virtual Reality Training Model for Post-Tensioning Construction: Framework and Application

by

Inwon Kim

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Engineering

Seoul National University

2023

Virtual Reality Training Model for Post-Tensioning Construction: Framework and Application

August 2023

Approved by Dissertation Committee:

Moonseo Park

Changbum Ahn

Thomas Kang

Virtual Reality Training Model for Post-Tensioning Construction: Framework and Application

지도교수 안 창 범

이 논문을 공학석사 학위논문으로 제출함

2023년 8월

서울대학교 대학원

건 축 학 과

김 인 원

김인원의 공학석사 학위논문을 인준함

2023年 8月

위 원 장 ______ 박 문 서 ______ (인)

부위원장 ______ 안 창 범 ______ (인)

위 원 ______ 강 현 구 ______ (인)

Abstract

The construction industry has been facing problems of low productivity and shortage of skilled workers. With the advent of new technologies such as virtual reality (VR), training programs with high training effectiveness have been developed, but the technology is not widely available and is not well utilized in the field. To address this research gap, this paper aimed to develop a VR training model for post-tensioning tasks based on a comprehensive framework for developing virtual reality (VR)-based technical training in the construction industry. The framework aimed to enhance the learning experience and effectiveness of technical training programs based on hierarchical task analysis (HTA). Through task analysis and implementation goals, a training program for post-tensioning tasks was designed, and essential functions were extracted to build a VR environment. The effectiveness of the VR training program was compared with traditional training methods, and the results showed that trainees who received technical training in a VR environment tended to have higher knowledge acquisition. In addition, a new training methodology of learning by observing VR users was proposed, which could solve the spatial limitations of VR training and provide training effects to more users. This study mainly focused on the tension-relieving process, and the findings may not be directly applicable to other technical training fields. Despite these limitations, the results of the study suggested that VR-based technical training has the potential to improve learning outcomes and overcome the challenges faced by traditional training approaches.

Keyword: VR Training; Post-tensioning; Hierarchical Task Analysis; Virtual Environment; Training Scenario Development

Student Number : 2021-22662

Table of Contents

List of Figures

List of Tables

Chapter 1. Introduction

1.1. Research Background

The construction industry is considered a major stimulant to economic growth and development by nations all over the world (Okoye et al., 2018). In South Korea, the construction industry is a vital sector, contributing approximately 5.2% to the national GDP (Bank of Korea, 2022). However, it has been consistently challenged by low productivity compared to other industries, primarily due to its labor-intensive nature (Hanna et al., 2008). The recent decline in the working-age population further exacerbates concerns about declining productivity. It was found that the supply of construction workers is 12.23% short of demand in Korea (Construction Workers Mutual Aid Association, 2022). Particularly among the worker responses, the response that skilled workers are lacking had far exceeded the response that it was appropriate, revealing that the shortage of skilled workers is a serious problem at construction sites (Almamlook et al., 2020).

The shortage of skilled technicians in the construction industry not only poses challenges in terms of manpower but also has a direct impact on productivity (Boadu et al., 2020). When there is a lack of experienced and skilled technicians, it can result in delays, errors, and inefficiencies in construction projects. Skilled technicians play a crucial role in ensuring the smooth execution of tasks, maintaining quality standards, and adhering to safety protocols (Bilau et al., 2015). Their expertise allows for effective problem-solving, efficient decision-making, and the implementation of best practices. Furthermore, with the recent advancements in AI and algorithms, the construction industry is also witnessing the introduction of various cutting-edge technologies such as robotics and autonomous vehicles (Jan et al., 2023). However, there is a shortage of skilled technicians who can effectively utilize these technologies in the construction sector.

The shortage of skilled technicians leads to increased pressure on the existing workforce, as they may have to take on additional responsibilities or work longer hours to compensate for the lack of skilled personnel (Dubois & Singh, 2009). This can contribute to fatigue, burnout, and decreased overall productivity. Moreover, inexperienced technicians may require more supervision and training, diverting the attention and resources of senior personnel from other critical tasks (Evans et al., 2007).

To address this productivity challenge, it is essential to invest in initiatives that promote the development of skilled technicians, to foster skilled manpower and strengthen safety measures in the construction industry. Efforts such as improving the education system and strengthening technical education are needed to nurture skilled manpower.

To improve the construction education system, immersive technologies such as virtual reality (VR) are gradually developing in the field of construction educational experiences, but they have only been developed for a limited number of trades and tasks. Furthermore, the developed training programs are not actively used in actual construction sites. Therefore, this paper aims to bridge this gap by proposing a framework for developing VR training models for construction workers. The paper also aims to analyze the potential impact that new skills training VR programs can have on the industry.

1.2. Problem Statement & Research Objectives

In this study, we propose a standard framework for developing VR technology-based training, develop a VR model based on it, and determine its practicality. We also propose a way to solve the spatial limitations of the developed VR training, and suggest the possibility of introducing it in practice at a large number of construction sites.

1.3. Research Framework

Based on the above considerations, this study aims to develop and verify a virtual reality tensile work training model of post-tensioning construction. The remainder of the paper is structured as follows: in Chapter 2, the theoretical background of the study is described and the methodology for VR training programs is analyzed in particular, introducing VR training in the construction field. In Chapters 3 and 4, we propose a framework for developing a VR training model based on task analysis, and develop a VR training program for post-tensioning tasks based on that framework. In Chapter 5, we verify the training effectiveness and motivation of the training program to validate its feasibility for use in the real world, and propose a new training methodology to address spatial limitations through the proposal of VR observer perspective training. Chapter 6 concludes the paper.

Chapter 2. Theoretical Background

2.1. Operational Skill Training with Virtual Reality

Successful operational skill training achieves its goals by incorporating customized training cadences that closely emulate real-world situations necessary for operational skills(Ward et al., 2006). This approach ensures trainees have ample opportunities for interaction and hands-on experiences, fostering their practical understanding(Grantcharov & Reznick, 2008). Additionally, the training program integrates a system of continuous feedback and evaluation, allowing for ongoing improvement and refinement of skills(Elnaga & Imran, 2013). However, Hands-on real-world training necessitates access to actual equipment or physical simulations, but conducting such training on the job poses heightened risks of reduced productivity, material damage, and injuries(Carruth, 2017). Therefore, to address these challenges and provide a safer and more effective training solution, virtual reality technology has emerged as a promising alternative(Zhao & Lucas, 2015).

VR technology has proven to be effective in delivering immersive training experiences and making training more realistic through virtual environments(Feng et al., 2020; Sacks et al., 2013). Also, Compared to a traditional training environment, virtual reality training provides a mistake-tolerant environment, alleviating the stress experienced by new hires while providing a cost-effective, replicable solution to meet your training needs(Mechlih, 2016). With these advantages, VR educational applications have been developed in a variety of domains, including natural disaster escape training(Farra et al., 2013; Smith & Ericson, 2009), surgical training(Beyer-Berjot et al., 2016; Palter & Grantcharov, 2010),and advanced education(Concannon et al., 2019; Pittman & LaViola, 2020). Recently, the advancements in haptic suits, interactive virtual reality (IVR), and other emerging technologies are driving increased interaction in VR environments, leading to the development of innovative educational techniques. These developments hold great potential for further enhancing training experiences and promoting immersive learning in VR.

2.2. Task Analysis for Development of VR Training

Task analysis plays a pivotal role in the development of VR training programs by systematically deconstructing complex tasks into discrete components. The primary aim of the task analysis was to determine the necessary information for a specific training task and compile a comprehensive list of elements that should be integrated into the training system during the design process (Kirwan & Ainsworth, 1992). This analytical process allows for the identification of specific knowledge and skills necessary for successful task execution, facilitating the design of targeted and effective training interventions (Crystal & Ellington, 2004).

One widely employed methodology for task analysis is the Hierarchical Task Analysis(HTA), which elucidates the hierarchical structure of tasks and the interrelationships between subtasks. HTA involves decomposing the procedure into a hierarchy of tasks and subtasks, delineating the overarching task goal, and expressing the relations among these tasks(Demirel et al., 2016). This process includes identifying subgoals, subtasks, and actions as part of the task decomposition process. Through the process of hierarchical decomposition, the identification and definition of specific knowledge and skills necessary for successful job performance are enabled, providing a solid foundation for the development of customized training programs that meet identified needs and requirements (Annett & Stanton, 2000).

Another prominent approach is Cognitive Task Analysis (CTA), which seeks to unveil the underlying cognitive processes and knowledge underlying task performance (Schraagen et al., 2000). CTA techniques encompass think-aloud protocols, interviews, and observations to elicit information on decision-making, problem-solving, and information processing strategies employed by domain experts (Crandall et al., 2006).

In addition, contextual inquiry and user observation provide valuable insights into current task execution practices within real-world settings (Fouskas et al., 2002; Gabbard et al., 1999). This entails immersing oneself in the trainees' work environments, observing their activities, and conducting interviews to grasp the contextual nuances, constraints, and challenges associated with the tasks (Laberge et al., 2014).

The information gleaned from task analysis serves as a foundational basis for informing the design of VR training programs. It aids in determining the appropriate content, scenarios, and interactive elements necessary to replicate real-world tasks within the virtual environment (Farmer, 1999). By focusing on the critical knowledge and skills requisite for task performance, task analysis enhances the transfer of learning from the VR training setting to the practical job context.

2.3. VR Training in Construction Industry

One of the primary applications of VR training in the construction industry is focused on enhancing safety. Trainees can encounter various hazards and challenging situations commonly found on construction sites, such as working at heights (Cyma-Wejchenig et al., 2020), operating machinery and robots (Tang & Yamada, 2011), or handling hazardous materials (Golovina et al., 2019). Through immersive VR experiences, construction workers can develop critical safety skills, including hazard identification, risk assessment, emergency response, and proper use of personal protective equipment (PPE). They can practice responding to emergencies, such as fires or accidents, without any real-life risks. Real-time feedback and behavior intervention within the VR environment help reinforce safe behaviors and correct any mistakes or improper actions(Kim et al., 2021).

Technical skill development is another crucial area where VR training finds significant application in the construction industry (Detsimas et al., 2016). Virtual reality technology offers construction workers an immersive and interactive learning environment to enhance their technical skills and competencies. Through realistic simulations, trainees can engage in hands-on experiences that replicate various construction tasks and operations. Adami et al. (2021) indicate that VR-based training was associated with a significant increase in knowledge, operational skills, and safety behavior compared to in-person training for robotic teleoperation. Osti et al. (2021) examined that VR training resulted in better retention, task performance, learning speed, and engagement than the video training counterpart for the wood construction workforce.

Due to advances in AI and algorithms, the construction industry is undergoing rapid changes with the emergence of new construction methods and equipment. To facilitate the swift adoption of these technologies in the field, there is a need for a universal framework for developing VR training models that can be widely implemented for the new technologies being developed.

2.4. Assessment and Evaluation Methods of Training

Evaluations of learning must be relevant and go beyond narrow measures of skills that lack sufficient predictive validity for success in life and work (Mulder, 2014). To fully understand the potential benefits of new educational technology, it is necessary to use a variety of assessment measures that cover a wide range of competencies, including knowledge, skills, and attitudes. The 4-level training evaluation model by Kirkpatrick (1998) is a commonly used framework for categorizing educational evaluation criteria. The first level includes the reaction criteria (Level 1), which assesses learners' impressions of the educational program. The second level is the learning criteria (Level 2), which evaluates how much knowledge learners have acquired from the educational program. The third level is the behavior criteria (Level 3), which measures how well the learned behaviors from the education are effectively transferred to real-life performance situations. The final level is the results criteria (Level 4), which measures how well the education is associated with organizational performance.

Numerous reviews and meta-analyses have been conducted comparing the introduction of virtual reality (VR) in training with traditional education and training methods, highlighting the advantages of simulation. According to research comparing the effectiveness of immersive VR with conventional training methods, immersive VR consistently demonstrated favorable outcomes in motivation factors such as enjoyment, motivation, and self-efficacy. However, the results regarding learning outcomes were inconsistent, with positive (Adami et al., 2021; Kim et al., 2021), mixed (Leder et al., 2019), and negative findings observed.(Parong & Mayer, 2018). The evaluation of VR training is predominantly limited to the first level, focusing on reactions and impressions. However, there is a lack of progress in conducting evaluations based on the four levels, including learning outcomes, behaviors, and results criteria.

Several studies are currently being conducted to evaluate the benefits of VR training, using researcher-centric evaluation methodologies that focus not only on educational outcomes, but also on the intrinsic motivation and cognitive load of participants(Makransky et al., 2019; Xi et al., 2023). Evaluation methodologies based on questionnaires are being utilized to assess the feasibility of implementing VR-based educational systems in real-world settings and to derive the necessary features and functionalities desired by users. These techniques are being applied to identify the practical applicability of VR training systems and to elicit the essential requirements from users. Based on these researches, we assess changes in intrinsic motivation alongside simple learning effects, using the aforementioned methodologies.

Chapter 3. Required Function for VR Training Program

As mentioned earlier, despite the need for extensive technical training in the construction industry, there is often a lack of effective training programs in place. Therefore, this study aims to develop and validate a VR training framework for the selected occupation of post-tensioning, which lacks a systematic training approach, despite being widely used in the construction industry.

As the demand for eco-friendliness and economic feasibility increases, and as long-span, slimming, and large-spanning of construction and civil engineering concrete structures progress, the cases of applying post-tensioning system to general buildings are increasing(Doan Kang & Seonghoe Lee. 2010). Therefore, it requires more specialized knowledge and practical experience of workers. Virtual reality training program would be economical in terms of time and cost as it doesn't use actual space and materials, and can be applied immediately at the construction site. Also, as there is no specific training program for post-tensioning work, it is expected that the VR training program will help improve the work efficiency.

In order to develop a VR training program for post-tensioning, it is essential to analyze the content that needs to be taught for training technicians in real-life construction sites and identify the implementation targets required for training skilled technicians. Therefore, this study aims to identify the content that requires training in the post-tensioning process, conduct task analysis to derive the process for the task, and determine the implementation targets within the VR training program based on the analysis results.

3.1. Post-Tensioning Construction

Post-tensioning system is a method that introduce a uniform tension to plural tendons imbedded in the concrete member after curing concrete, so inducing compressive force at the lower end of a member that receive tensile force. Therefore, the key aspect of this task is applying tensile force to tendon.

Post-tensioning construction procedure is largely composed of three steps: laying, stressing, and grouting(Corven & Moreton, 2013). First in laying, form work is performed according to shop drawing, and bottom reinforcement is placed along the designed diameter and spacing. Then, the strand cut to a proper length is inserted into the duct, the profile chair and the grout hose are fixed before pouring the concrete. In the stressing stage after concrete curing, the strands are tensioned using hydraulic equipment to achieve the target elongation and concrete strength. Different stressing method is applied depending on whether the post-tension construction is bonded or unbonded. Bonded post-tensioning construction is generally used for bridges or beams under heavy loads, while unbonded post-tensioning construction is used in slabs, beams, and walls of general buildings. Bonded post-tension construction primarily involves the use of large equipment, which results in a relatively lower need for training. However, unbonded post-tension construction requires training due to the utilization of handed equipment. Therefore in this study, tensile work of unbonded post-tensioning construction is set as the target work so the mono-strand tensioning work process is dealt with. In the grouting step, grout is mixed and injected into the tendon inlet hose, then when the required pressure is reached the suction hose is locked. The whole procedure is carried out on site, and the overall unbonded post-tensioning process is in Figure 3-1.

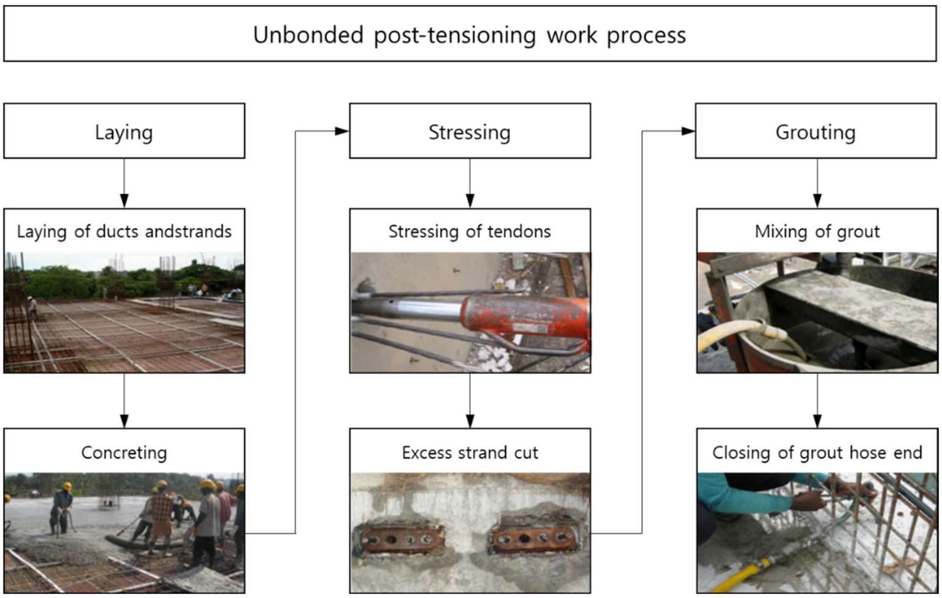


Figure 3-1. Work process of unbonded post-tensioning construction

Uneven tensile force generated in the post-tension member during the construction process may lead to steel wire and edge rupture and concrete failure due to excessive stress or less than expected strength. Therefore, measuring the exact tension applied to each tendon requires high accuracy(Shin & Kang, 2018.)

Currently, in most post-tension construction sites, the tensile force and elongation are measured by an analog method in which the operator measures the pressure gauge of the hydraulic pump and the elongation of the hydraulic jack during tensioning work(S. H. Park & Kang, 2020). In this analog method, time delay occurs because an operator has to control the hydraulic post-tension equipment and measure at the same time, and the accuracy of the measured tension force is greatly affected by the proficiency of the operator(S. Park & Kang, 2020). In addition, the use of hydraulic equipment by unskilled workers may lead to safety accidents. From 2012 to 2022, 36 hydraulic jack accidents occurred in the United States, resulting in a fatality rate of 47%(Occupational Safety and Health Administration. n. d.). Therefore, for the reliability of the tensioned member as well as for the safety of workers, it is necessary to provide workers proper tensioning work training program for higher proficiency.

Skill training for post-tensioning work is conducted in the field as an apprenticeship, and it takes some time for workers to become proficient. In particular, although the tensioning work requires the highest proficiency is a simultaneous work of applying tension to the tendon and measuring it at the same time, there isn't specific training program for the reason that the hydraulic equipment is simple to use. In order to respond to the increasing demand for the post-tension method, a process is needed to train workers with high proficiency in tensioning work through multiple hands-on experience in a short period of time. However, training with actual concrete members and tendons has a limitation that requires high cost. VR training can be utilized to develop an efficient educational process, and to achieve this, a process of identifying implementation targets based on Hierarchical Task Analysis(HTA) is conducted.

3.2. Hierarchical Task Analysis of stressing work procedure for post-tensioning training model

This study aims to develop a training model for systematic training related to the successful performance of tensile work procedure of post-tensioning construction. To create an effective VR training program, it is crucial to analyze the actions of workers in the actual worksite and select the targets to be implemented in the virtual environment on a behavioral level. HTA was performed to analyze the relationship between key indicators and detailed tasks. The ultimate goal is to equip workers with the skills needed in the field.

The HTA analysis of the tensioning operation yielded the following results (Figure 3-2). It consists of three main stages: 1) Initiate procedure, 2) Stress the strand, and 3) Equipment removal and finishing. The Initiate procedure can be further divided into the preparation stage and the equipment connection stage. In the preparation stage, the work area around the strand is cleared, and paint marks are applied for elongation measurement after wedge insertion. In the equipment connection stage, the hydraulic jack is moved upward onto the target strand for connection. Moving on to the stress the strand stage, the hydraulic pump lever is adjusted to measure the pressure gauge and elongation repeatedly until the target elongation is reached. Once the target elongation is achieved, the lever is returned to its original position. Lastly, in the equipment removal and finishing stage, the hydraulic jack is first removed, followed by the process of excess strand cut. It is ensured that the hydraulic jack head is completely in place before removing the equipment upward from the strand, like step 1.2. Afterward, the excess tendon is cut, and the tensile work is completed.

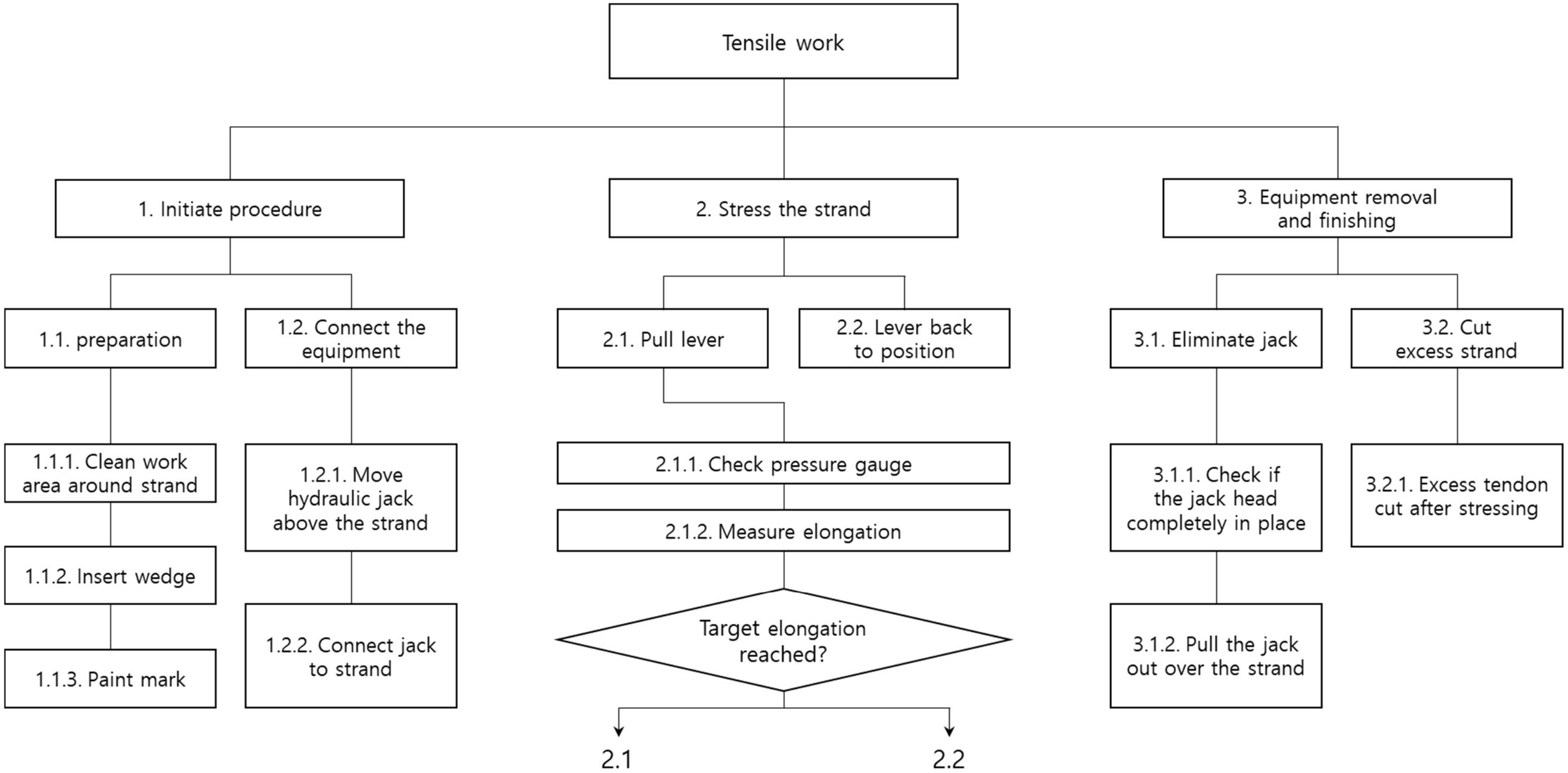


Figure 3-2. Hierarchical Task Analysis of post-tensioning tensile work

The detailed HTA model focusing on the stressing operation using hydraulic equipment is as follows.(Figure 3-3) The stressing operation involves adjusting the lever and testing the elongation repeatedly until the target elongation is reached. The worker continuously checks if the target elongation has been achieved, and if not, adjusts the lever and measures the elongation again. The lever control consists of three specific stages: test lever state, pull lever, and lever back to position. The decision to pull the lever or return it to its original position depends on whether additional pressure needs to be applied for the equipment to operate.

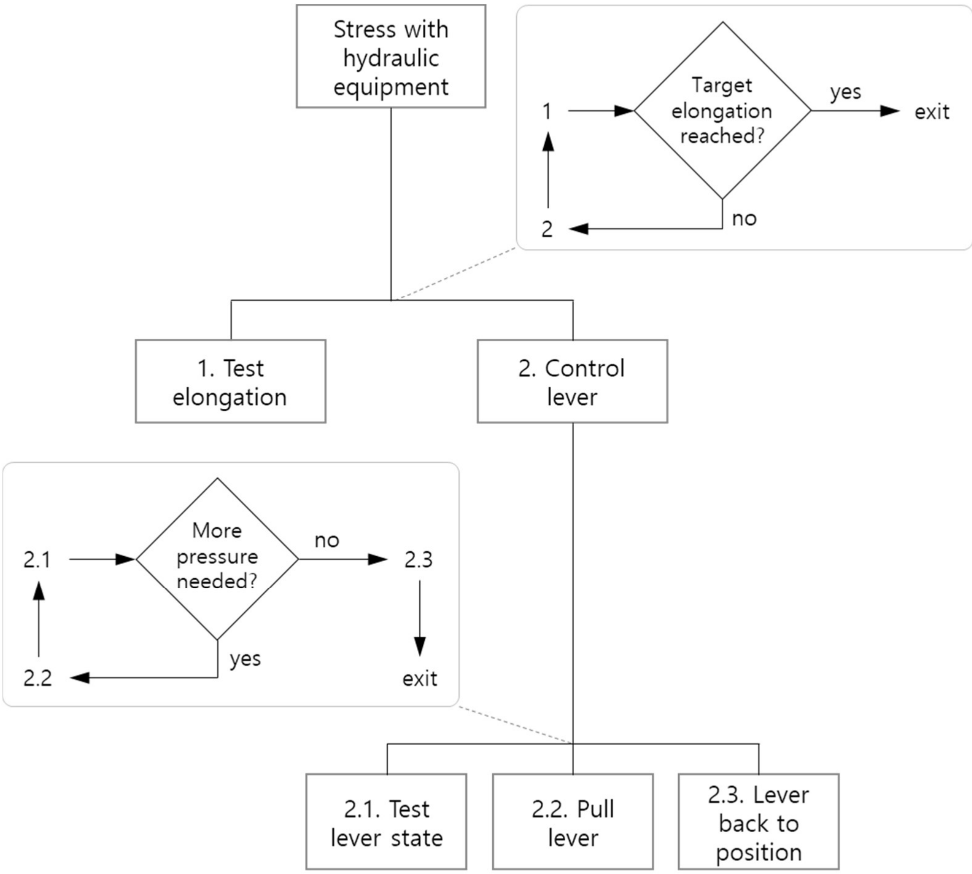


Figure 3-3. Detailed HTA of stressing process with hydraulic equipment

3.3. Implementation Object and Required Function Derivation

Based on the analysis conducted in section 3.2, the objects to be implemented and the required interactions for each step have been derived. The preparation and cut strand stages within the stressing step are simple tasks that do not involve the use of hydraulic equipment, and they have been excluded from the training target as they are considered to have low educational impact due to the absence of variables such as unexpected situations, difficulties, or risks. It is concluded that focused training on the use of hydraulic equipment, which can pose significant risks and compromise the integrity of the structure if operated incorrectly, is necessary.

Therefore, the training program has been designed to focus on the processes involving hydraulic equipment. Through a detailed analysis of each sub-task, the objects and interactions requiring implementation have been identified. In step 1.2, the hydraulic jack should be prepared along with the wedge-anchored strand, and the worker performs the task of carrying the hydraulic jack and connecting it to the strand. In steps 2.1 and 2.2, the worker interacts with the hydraulic jack and pressure gauge by pulling the lever and returning it to its original position. This interaction directly affects the task outcome and should be implemented in the most realistic manner. Finally, in step 3.1, the worker removes the jack from the strand after completing the stressing. Detailed analysis of the interactions can be found in Table 3-1.

<table>
<tr><th colspan="2">Tasks</th><th>Objects</th><th>Interaction</th></tr>
<tr><td rowspan="2">1.2 connect the equipment</td><td>1.2.1. Move hydraulic jack above the strand</td><td rowspan="2">• Hydraulic jack
• Strand(tendon)
• Wedge</td><td>• Worker grab the jack and move to task place</td></tr>
<tr><td>1.2.2. Connect jack to strand</td><td>• Hydraulic jack body and strand attached when connected</td></tr>
<tr><td rowspan="2">2.1. pull the lever</td><td>2.1.1. check pressure gauge</td><td rowspan="3">• Hydraulic jack
- head
- body
• Pump
- lever
- pressure gauge
- needle
• Ruler
• Strand</td><td>• Worker grab the lever and pull to give pressure to equipment
• Needle rotates on the pressure gauge as the lever pulled</td></tr>
<tr><td>2.1.2.measure elongation</td><td>• Hydraulic jack body moves backward as the lever pulled
• Worker grab the ruler and measure the stressed length(elongation)</td></tr>
<tr><td colspan="2">2.2. lever back to position</td><td>• Worker grab the lever and rotate back to its position
• Hydraulic jack head move toward the body</td></tr>
<tr><td rowspan="2">3.1. eliminate jack</td><td>3.1.1. check if the jack head completely in place</td><td rowspan="2">• Hydraulic jack
- head
- body
• Strand</td><td>• Hydraulic jack disconnected from strand
• Worker check the position of the hydraulic jack's head and body</td></tr>
<tr><td>3.1.2. Pull the jack out over the strand</td><td>• Worker grab the jack and eliminate</td></tr>
</table>

Table 3-1. Implementation objects and required interaction analysis by tasks

Chapter 4. VR Training Model for Post-Tensioning Construction

Following Chapter 3, the target objects and required functionalities were identified through Hierarchical Task Analysis (HTA). The next step is to select the software and device hardware to establish the foundational environment for implementation. The identified required functionalities, including objects, interaction methods, and data input/output, were then implemented.

4.1. Development Environment

The VR training model was developed using the Unity3D game engine, with the editor version of 2021.3.3f1. In order to implement the post-tensioning work, a virtual construction site similar to the actual working environment including concrete members and static/dynamic obstacles was created. The interaction of the equipment was programmed using the C# programming language. Trainees interact with the virtual environment and objects through Meta Quest2.

4.2. Required Function Implementation

Based on the analyzed task procedures and identified required functionalities from Chapter 3, the virtual environment was implemented. It consists of the following functionalities within the virtual environment: Construction Site Background and Tensioning Work Environment, Post-Tensioning Equipment, and Data Input/Output

.

4.2.1. Construction Site Background and Tensioning Work Environment

Due to the outdoor nature of construction sites, weather conditions have a significant impact on the visual fidelity of the site. Since post-tensioning work is not performed in adverse weather conditions such as rain or snow, the scope of implementation is limited to the changes in sunlight intensity and cloud variations. To simulate training in various weather conditions, the implementation includes changes in light intensity and direction based on the sunlight's illuminance, altitude, and azimuth. Additionally, the amount of clouds within the site is parameterized to simulate changes in lighting conditions.

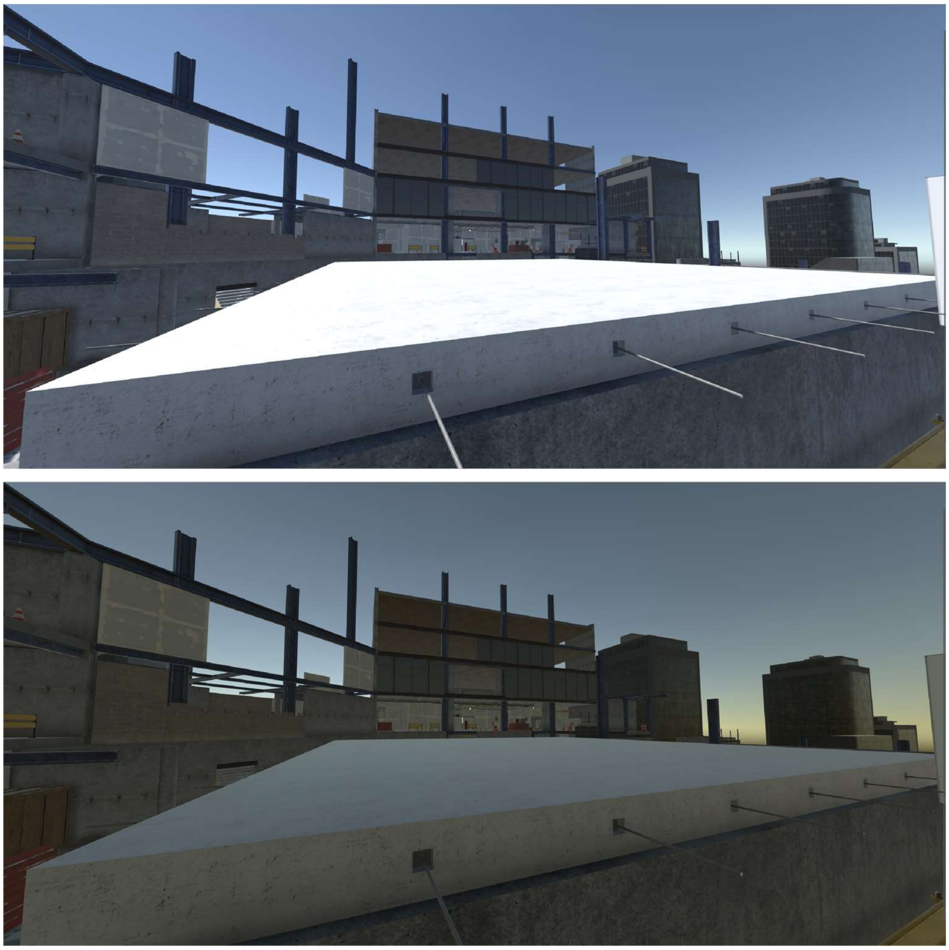


Figure 4-1. Perspective view of virtual environment by light change

The virtual training space consists of the Tensioning work environment where the education takes place, and the construction site background that surrounds this environment. To enhance user immersion, the construction site background is designed to resemble an actual construction site, featuring a three-story building under construction. Various construction equipment such as crane and truck are placed within the site, along with safety facilities. Additionally, recorded ambient sounds from real construction sites are incorporated into the background to create a realistic atmosphere and enhance participant engagement. All components of background construction site environment was created with SketchUp.

Figure 4-2. Virtual environment configuration

(a) Background construction site, (b) post-tensioning work space

4.2.2. Post-Tensioning Equipment

The equipment used in Post-Tensioning operations includes hydraulic jacks and hydraulic pumps, which interact with the embedded steel reinforcement within the slab. To achieve a high educational impact, it is essential for these equipment and objects to be implemented in a manner that closely resembles reality. A thickness of 200mm post-tension concrete slab and SWPC 7BL strand with diameter of 15.2mm was used in the model.

The hydraulic jack and hydraulic pump used in post-tensioning construction have been implemented. Sharp3D was used for modeling, and Blender was employed to incorporate materials such as metal and rubber. The hydraulic jack is connected to the hydraulic pump via a rubber hose. By rotating the lever located on the hydraulic pump in a clockwise direction, the pressure gauge on the pump increases, simultaneously pulling the hydraulic jack and allowing the tensioning operation to proceed. To facilitate this functionality, a C#-based script was developed.

```
public class JackBody : MonoBehaviour
{
    private float power;
    [SerializeField]private float speed;
    [SerializeField] private Transform body;


    void Update()
    {
        this.transform.localPosition = new Vector3
        (this.transform.localPosition.x - speed/100 * power *
        Time.deltaTime,0, 0);
        if (power == 0)
        {
            if (-0.0613f != this.transform.localPosition.x)
            {
                body.transform.localPosition = new Vector3
               (body.transform.localPosition.x - speed / 100 * 50
               * Time.deltaTime, 0, 0.09050003f);
                this.transform.localPosition = new Vector3
               (this.transform.localPosition.x + speed / 100 * 50
               * Time.deltaTime, 0, 0);
                if (-0.0613f < this.transform.localPosition.x)
                {
                    this.transform.localPosition = new Vector3
                   (-0.0613f, 0, 0);
                }
            }
        }
    }

    public void GetPower(float p)
    {
        power = p;
    }
```

```
    public void ResetParts()
    {
        body.transform.localPosition = new Vector3(0.2651f, 0,
        0.09050003f);
    }
}
```
Figure 4-3. Hydraulic jack body transform script

```
public class Rotationchange : MonoBehaviour
{
    private float power;
    [SerializeField] private float speed;

    void Update()
    {
        Debug.Log(160 / 100 * power);
        if (this.transform.localRotation.eulerAngles.z < 160 /
        100 * power)
        {
            this.transform.localRotation = Quaternion.Euler(0, 0,
           this.transform.localRotation.eulerAngles.z+ speed *
           Time.deltaTime);
        }
        else if(this.transform.localRotation.eulerAngles.z > 160
        / 100 * power)
            {
            this.transform.localRotation = Quaternion.Euler(0, 0,
           this.transform.localRotation.eulerAngles.z - speed *
           Time.deltaTime);
        }
    }

    public void GetPower(float p)
    {
        power = p;
    }
}
```

Figure 4-4. Hydraulic pump needle rotation script

```
public class Check : MonoBehaviour
{
    private bool isActive = false;
    [SerializeField] private UnityEvent Events;
    [SerializeField] private Transform target;
    [SerializeField] private float first;
    [SerializeField] private float last;
    [SerializeField] private UnityEvent ClearEvent;
    [SerializeField] private UnityEvent MissEvent;
    [SerializeField] private TMP_Text clear;
    [SerializeField] private TMP_Text miss;


    void Update()
    {
        if (isActive)
        {
            this.transform.position =new Vector3
           (this.transform.position.x,
           this.transform.position.y ,
           target.transform.position.z);
        }
    }

    public void Active()
    {
        if (isActive == false)
        {
            Events.Invoke();
        }
        isActive = true;
    }
```

```
    public void Deactive()
    {
        isActive = false;

            if (first < this.transform.position.z + 0.3234f &&
            this.transform.position.z + 0.3234f < last)
            {
                ClearEvent.Invoke();
                clear.text = (((this.transform.position.z +
                0.3234f)*100).ToString());
                Debug.Log("c");
            }
        else
        {
            MissEvent.Invoke();
            miss.text = (((this.transform.position.z +
            0.3234f)*100).ToString());
            Debug.Log("m");
        }
    }
}
```

Figure 4-5. Work success/failure check and print script

4.2.3. Data Input/Output

The model was designed to measure if the operation was successfully done through two output data, the elongation and the maximum pressure during the operation. The standards of the two data were set based on the values of actual post-tensioning work. For the 15m*15m post-tension concrete slab with a thickness of 200mm implemented in the VR training model, the target elongation is 10.16cm and an error of +/- 7%, which is a generally accepted range, is applied to set 9.3 to 10.7cm as the operation success criterion range(Post-Tensioning Institute, Frequently Asked Questions Field Elongation Measurements, 2007). We can get the elongation by measuring the distance between the body and the head of the hydraulic jack using a ruler. The elongation and maximum pressure are displayed above the strand along with the success or failure of the work when the hydraulic jack is removed from the strand. Elongation is calculated by the difference of the initial position of the strand and the ending position. For the maximum pressure, the pressure when the gauge needle rotates the most is the output.

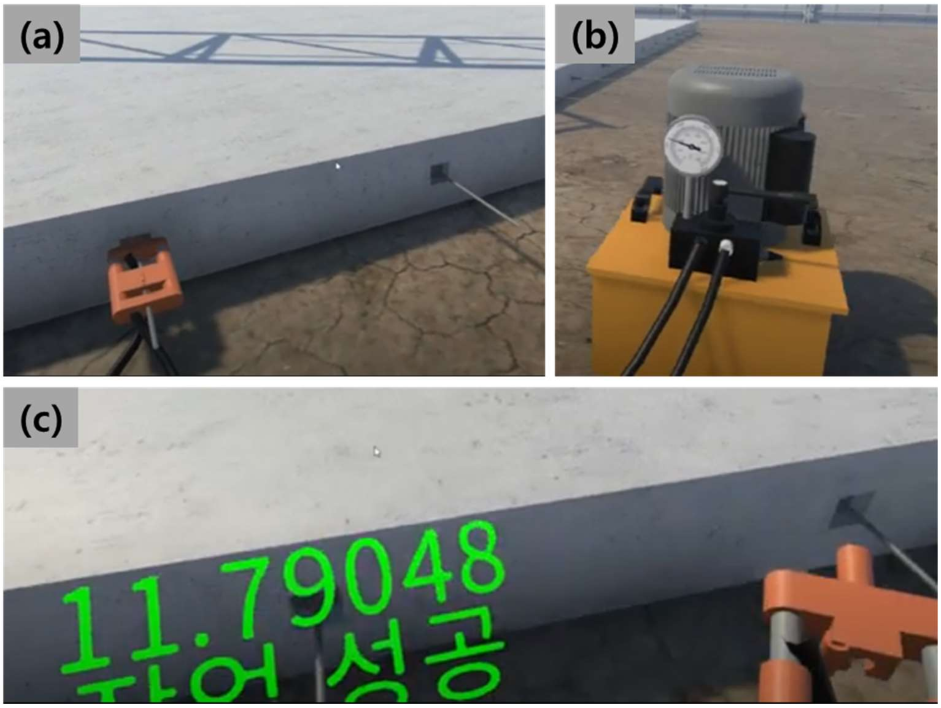


Figure 4-6. Equipment interaction implementation

(a) Jack connection, (b) Pump lever and gauge interaction, (c) Result

4.3. Training Scenario for Post-tensioning

The training session is structured as follows: When the training starts, users follow the guidance of a virtual voice conductor located next to the workspace screen to carry out the practice. The screen in front of the workspace presents explanations of theoretical content related to the ongoing work, and explanations of the content are presented auditorily. Participants will use the trigger button to grab the hydraulic jack and attach it to the rebar embedded in the slab. They will then check the target length and pressure limit before rotating the lever on the hydraulic pump in a clockwise direction to initiate the tensioning operation. After completing the tensioning process by rotating the lever in the counterclockwise direction to release the pressure, the results of the operation and the success of the task will be displayed on the screen. Participants will repeat this process for a certain number of iterations to complete the training, and the final results will be presented on the screen. By analyzing the obtained results, participants can evaluate the accuracy of their work and identify any errors.

Chapter 5. Training Model Verification: Motivation and Learning Effect

In the examination of the development of a VR training program for post-tensioning construction, the focus of our study was placed on the identification of required functions through HTA and the derivation of the implementation object and necessary functions for the training model. This framework was utilized to create a VR training model specifically tailored for post-tensioning construction. To validate the Interactive VR training program developed using the aforementioned framework, we compared the program with the traditional screen and document-based training to analyze the impact of the program on engagement and motivation in the context of post-tensioning processes. In addition, we tested the feasibility of replacing traditional training method with VR-based training on a construction site based on training effectiveness and motivation.

5.1. Theory and predictions for VR observer

While many studies have shown the effectiveness of using VR to teach skills on construction sites, these findings are not directly applicable to the construction industry because VR is not a suitable form of training for the large, labor-intensive environment of a construction site. In order to efficiently train all construction workers on a site, multiple trainers are required to train simultaneously to ensure that the minimum level of knowledge desired by the trainer is met. However, behavior-based VR training is difficult to train a large number of people, making it difficult to deliver the level of knowledge desired by site managers.

Training using VR delivers relevant knowledge and experiences to VR users through visual and auditory stimuli. VR training based on the following audiovisual stimuli can provide observers with an experience similar to traditional video and screen-based training. If observing people using VR can produce similar training effects to traditional training, there is no need to equip every trainer with VR equipment, which suggests the possibility of mass training of workers using VR.

Therefore, this study aims to analyze the effectiveness of education from the perspective of observing users using VR, and for this purpose, the following hypotheses were established:

H1. People who observe VR users demonstrate higher educational performance compared to those who receive traditional education.

H2. People who observe VR users have higher motivation compared to those who receive traditional education.

While verifying the above hypotheses, we confirm whether there is an improvement in the educational effects and motivation of the group using VR.

5.2. Method

The sample consisted of 26 undergraduate and graduate students (18 males and 8 females) who were studying architecture engineering at a large Korean university. The majority of the students ranged from 23 to 31 years of age (mean age = 25.5). Students participated in a post-tensioning training program to prepare their knowledge and use of tensioning operations. Participants were randomly divided into one of three treatment groups for training: traditional (n = 8), VR (n = 9), and VR observers (n = 9).

5.2.1 Experiment Procedure

The students participating in the experiment were randomly assigned to three educational conditions: traditional, VR, and VR observer. The traditional group underwent one-on-one instruction with a teacher, while the VR and VR observer groups formed pairs and received education with a VR instructor. Each education session lasted for 15 minutes. After receiving traditional, VR, or VR observer education, all students immediately took a post test on the relevant knowledge and were surveyed on their intrinsic motivation towards the learning and post-attention tasks.

5.2.2 Materials

The materials used in the study included a text-based post-tensioning manual, an immersive VR version of a post-tensioning training simulation, and posttest participant questionnaire. Text-based post-tensioning material and posttest participant questionnaire are in appendix.

Text-based post-tensioning manual

The text training material consisted of a 4-page manual that was designed based on learning materials of Post-Tensioning Institute and VSL. The main learning objective of the manual was knowledge about unbonded post tensioning installation, operating the tensioning equipment, and safety skills. Three types of knowledge based on learning materials of Post-Tensioning Institute and VSL were the focus of the Text-based manual including facts (e.g., the definition of post-tensioning work and difference between bonded / unbonded strand system), procedures (e.g., the step by step process of stretching the strand), and safety rules (e.g., How to use the right equipment and PPE). The instructional materials were developed under the review of three experts specializing in post-tension.

VR post-tensioning training

In a VR environment, paricipants need to acquire the theoretical background of the content while practicing using virtual equipment. Therefore, we reorganized the text-based training content in the form of bullet points for users to see by forming a virtual blackboard around the workspace. In addition, to deliver information based on hearing, we used Naver clova dubbing API to create a virtual voice to explain the text-based explanation and include it in the training.

Posttest participant questionnaire

After the experiment, participants will immediately submit two surveys: A multiple-choice quiz to assess educational achievement, and an intrinsic motivation inventory (IMI) to measure the degree of motivation.

The educational achievement assessment quiz consists of a 20-question multiple-choice quiz with content that is fully embedded in the training content and broadly covers the main learning objectives described above. The quiz was also developed and reviewed by three post-tenure experts.

To measure participants' motivation, we used the Intrinsic Motivation Inventory. The Intrinsic Motivation Inventory (IMI) is a tool used to measure participants' intrinsic motivation in VR training (McAuley et al., 1989). IMI assesses the extent to which individuals are interested in and engaged with a specific activity due to internal motivations. By using the IMI, we can gain a better understanding of the individual aspects of motivation among VR training participants (Lin & Wang, 2021). IMI have 7 scales: Interest/Enjoyment, Perceived Competence, Effort/Importance, Pressure/Tension, Perceived Choice, Value/Usefulness, and Relatedness. In this study, we excluded the items of perceived choice and relatedness, which were not relevant to this training, and evaluated the remaining five items. The IMI questionnaire consisted of 24 items, and participants submitted their responses on a 7-point Likert scale.

5.3. Results

Hypothesis 1: Educational performance

The first prediction is that students in the VR perspective groups will report higher levels of educational performance compared with students in the traditional group. The top line of Table 5-1 shows the mean score (and standard deviation) for the three groups. A one-way between-subject ANOVA showed that there was a significant difference among the three training conditions in their educational performance, $F(2, 23) = 3.222$, $p = 0.058$. However, the p-value is slightly above the conventional threshold of 0.05 for statistical significance, this suggests that there may be a trend towards a difference in educational performance among the three training conditions.

Hypothesis measure	**Group**			**p-value**
	Traditional	**VR**	**VR observer**	
Score	59.13(9.18)	69.11(9.80)	60.44(7.63)	0.058
Interest/Enjoyment	4.16(1.30)	4.78(1.42)	4.03(1.64)	0.522
Perceived Competence	4.04(0.75)	3.98(1.23)	4.11(1.24)	0.97
Effort/Importance	4.5(0.60)	4.58(1.14)	3.92(0.92)	0.097
Pressure/Tension	1.66(1.03)	2.25(0.89)	1.69(0.77)	0.319
Value/Usefulness	5.21(1.18)	5.15(0.92)	4.85(1.12)	0.762

Table 5-1. Mean and standard deviation on the six dependent measures for three groups

Post hoc analyses using the Welch two sample t-test between each group indicated that the VR group ($M = 69.11$, $SD = 9.80$) scored significantly higher than the traditional group ($M = 59.13$, $SD = 9.18$); $t(14.93) = -2.16$, $p = 0.048$. The effect size (d) was −1.04, considered large by Cohen (2013). Also, the VR group may scored higher than VR observer group (M = 60.44, SD = 7.63); $t(15.09) = -2.16$, $p = 0.054$. The effect size (d) was −0.99, considered large. However, There was no statistical difference between the traditional group and the VR observer group; $t(13.64) = -0.32$, $p = 0.755$. All the result is present in Table 5.2. Through these results, it was confirmed that the group that received education using VR showed higher educational effects compared to the other two groups. In addition, the group that received traditional education and the group that observed VR users showed similar educational effects, which is contrary to the hypothesis of Hypothesis 1.

Groups	**t**	**p-value**	**Cohen's d (effect size)**
Traditional & VR	-2.16	0.048	-1.04 (large)
Traditional & VR observer	-0.32	0.755	-0.16 (negligible)
VR & VR observer	-2.09	0.054	-0.99 (large)

Table 5-2. Learning Effect of groups by score: paired sample t-test and effect size

Hypothesis 2: Motivation

The second prediction is that students in the VR perspective groups will report higher level of motivation compared with students in the traditional group. The top line of Table 5-1 shows the mean score (and standard deviation) of Interest/Enjoyment, Perceived Competence, Effort/Importance, Pressure/Tension, Value/Useful-ness for the three groups. A one-way between-subject ANOVA showed that there was no significant difference among the three training conditions in their Interest/Enjoyment; $F(2, 23) = 0.668$, $p = 0.522$, Perceived Competence; $F(2, 23) = 0.031$, $p = 0.97$, Pressure/Tension; $F(2, 23) = 1.20$, $p = 0.32$, and Value/Usefulness; $F(2, 23) = 0.28$, $p = 0.76$. For Effort/Importance, the data does not follow a normal distribution because it fails the Shapiro-Wilk normality test ($p < 0.05$), and Kruskal-Wallis rank sum test showed that there was weak statistical evidence that mean differences may exist between groups ($p = 0.097 < 0.1$). Through these results, it was suggested that there was no difference in motivation among all groups regardless of the education method, but there may be a possibility of differences in Effort/Importance among each group.

One participant in the VR group submitted significantly low level response for Effort/Importance (participant 12, 2.5), and this participant may have acted as an outlier. The fact that the effect sizes between the VR and VR observer groups(d = -0.64) and the VR and traditional groups(d = -0.74) were larger than the effect sizes between the

VR and traditional groups(d = -0.09) suggests that the VR observer group may have had lower Effort/Importance than the other groups.

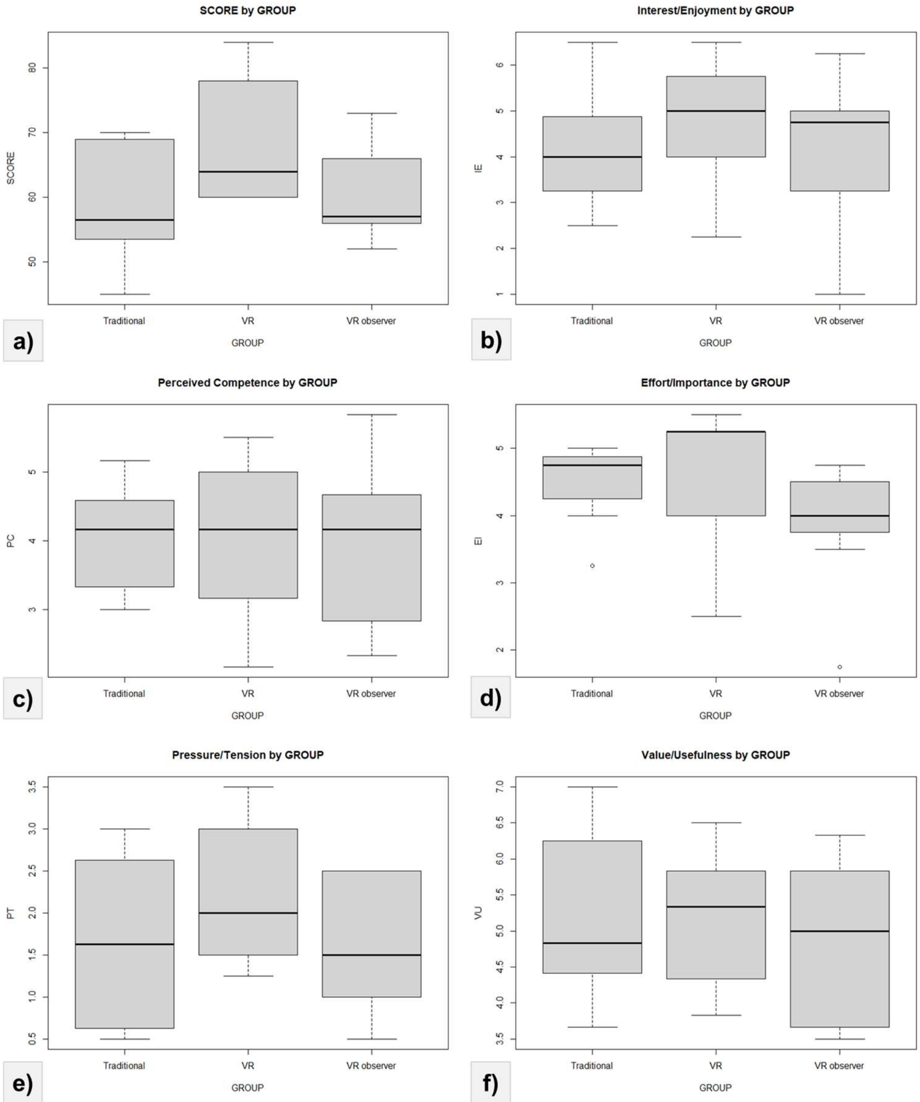


Figure 5-1. Box plot graph by group. a) Score, b) Interest/Enjoyment, c) Perceived Competence, d) Effort/Importance, e) Pressure/Tension, f) Value/Usefulness

Educational performance and Motivation

Based on the results collected in this experiment, we analyzed the correlation between Educational performance and intrinsic motivation to derive improvements in technical education. To this end, we evaluated the extent to which the elements of intrinsic motivation affect learning outcomes by creating a multiple regression model that predicts scores based on the elements of the IMI. First, to assess the presence of multicollinearity among the predictor variables, variance inflation factors (VIFs) were calculated for each predictor. The VIF values for Interest/Enjoyment, Perceived Competence, Effort/Importance, Pressure/Tension, and Value/Usefulness were 2.55, 1.86, 1.76, 1.59, and 2.95, respectively. All VIF values were below the commonly used threshold of 10, indicating that multicollinearity was not a major concern in the model.

A stepwise multiple linear regression was conducted to examine the relationship between educational performance (Score) and the five elements of the Intrinsic Motivation Inventory. The results of the stepwise regression indicated that two predictors, Pressure/Tension (PT) and Interest/Enjoyment (IE), were retained in the final model. The final model explained 26.5% of the variance in score ($R^2 = .265$, $F(2,23) = 4.15$, $p = .029$). The analysis revealed that PT significantly predicted score ($\beta = 5.80$, $t(23) = 2.84$, $p = .009$), indicating that for every one-unit increase in PT, there was an associated increase of 5.80 units in score, while holding IE constant. IE was not found to be a significant predictor of score. The equation for the multiple regression model is as follows:

$$\hat{y} = 44.15 + 1.85IE + 5.80PT \quad \textbf{(1)}$$

Where $\hat{y}$ = dependent variable (score), 44.15 is the y-intercept, 1.85 is the regression coefficient for IE, and 5.80 is the regression coefficient for PT. The coefficients represent the change in the dependent variable for a one-unit change in the corresponding independent variable, while holding all other independent variables constant.

Coefficient	**Estimates**	**SE**	***p*-value**
B_0, Intercept	44.15	7.95	<0.01*
B_1, Interest/Enjoyment	1.85	2.04	<0.01*
B_2, Pressure/Tension	5.80	1.28	0.16

Table 5-3. Regression coefficients, indicating the influence of intrinsic motivation factors on Educational performance. * Significant at the p < 0.05 level; and SE = standard error.

5.4. Discussion

The main research results related to learning effects and motivation are that students who received technical training in a VR environment tend to have higher knowledge acquisition than students who learned through traditional media, and findings are consistent with several studies that have identified positive pretest-to-posttest changes in learning effect while using VR simulations (e.g. Adami et al., 2021; Concannon et al., 2019; Lin & Wang, 2021). Despite the content of traditional paper-based educational materials and education provided in a VR environment being identical, higher performance was achieved during the same education time. The experimenters internalized the theoretical content related to the task by interacting with pre-designed objects in the VR environment and learning the operating principles of the equipment, which led to high educational effectiveness. Although cognitive overload could occur due to the addition of visual and auditory stimuli along with behavior, leading to a decrease in learning effectiveness, there was no problem with cognitive overload in accepting stimuli that included narratives about the actions currently being performed by the experimenter. The need for this framework, which analyzes behavior through HTA and implements interaction to minimize the gap between knowledge transfer due to visual and auditory stimuli and behavior when creating VR models for technical education, was indirectly derived.

We also explored the potential of a newly proposed method of providing education by observing VR users. This idea was proposed as a methodology for maintaining the high educational effectiveness of VR while providing education to many people at once in a classroom-style educational setting as in traditional education, but without the need for instructors. As a result of analysis through group comparison, it was confirmed that the education method of observing VR users had the same level of learning effect as traditional screen and text-based education. In addition, it was confirmed that the effort/importance factor of motivation was observed at a lower level in the group receiving education by observing VR users compared to other groups. This may be due to the interaction with educators and the environment, which is satisfied in traditional education, being simplified into a form of visual and auditory observation and transformed into a general form of transmission. In addition, it may be considered as a decrease in motivation due to changes in perception caused by the change from being a part of the subject of education to being an observer. To improve this, we derived additional suggestions to proceed with changes to the role of subjects within the educational environment by adding new interactions with surrounding observers and VR users, not just simple observations.

The results of the experiment derived the correlation between score and intrinsic motivation factors, analyzing the motivation factors that should be considered important in future education. Through stepwise multiple linear regression, it was confirmed that score and Pressure/Tension had a strong correlation, and although not statistically verified, Interest/Enjoyment (IE) was found to have a complementary correlation. The regression model composed of these two variables only explains 26.5% of the variance in educational effectiveness, but it shows high statistical reliability ($R^2 = .265$, $F(2,23) = 4.15$, $p = .029$). This suggests that an individual's motivation, including Pressure/Tension and Interest/Enjoyment, can affect the outcome of education, but this can be considered as a side effect of factors that affect learning, such as the participant's basic knowledge level, comprehension, cognitive ability, and memory. Therefore, it is suggested that the development of educational programs that can provide high Pressure/Tension regardless of the form of education is necessary to derive high educational performance overall while considering individual differences.

Lastly, there are limitations to the results proposed in this study. The experiment was conducted in a laboratory VR environment and was not conducted on post-tensioning education subjects at actual construction sites. Education in virtual reality has affected knowledge levels, but it needs to be verified whether it can affect behavior and change in actual reality. Therefore, verification at the site is necessary, including the aforementioned additional improvement measures.

Chapter 6. Conclusion

6.1. Conclusion & Contribution

In this study, we proposed an HTA-based framework for the development of VR-based technical education. To verify the framework, we identified the work analysis and implementation targets for the tensioning process, which is widely used in the construction industry but requires a lot of labor. Through this, we designed an education program for tensioning work and extracted essential features and functions to implement a VR environment. We verified whether the VR education developed based on this framework had a difference in learning effect compared to traditional education. In addition, we proposed learning through observing VR users as an educational methodology that can provide VR-like educational effects to many users while solving the spatial limitations of VR education that make it difficult to introduce it to the field.

The results suggest that students who received technical training in a VR environment tend to have higher knowledge acquisition than students who learned through traditional media. This is consistent with several studies that have identified positive changes in learning effect while using VR simulations. The experimenters were able to achieve high educational effectiveness by internalizing the theoretical content related to the task through interaction with pre-designed objects in the VR environment. A newly proposed method of providing education by observing VR users was also explored, and it was found to have the same level of learning effect as traditional screen and text-based education. The results of a stepwise multiple linear regression analysis showed that score and Pressure/Tension had a strong correlation, and although not statistically verified, Interest/Enjoyment was found to have a complementary correlation. This suggests that an individual's motivation can affect the outcome of education, but this can be considered as a side effect of factors that affect learning. Therefore, it is suggested that the development of educational programs that can provide high Pressure/Tension is necessary to derive high educational performance overall while considering individual differences.

6.2. Limitation & Future Study

One limitation of the current study is that the experiment was conducted in a laboratory VR environment and not on post-tensioning education subjects at actual construction sites. While education in virtual reality has affected knowledge levels, it needs to be verified whether it can affect behavior and change in actual reality. Therefore, verification at the site is necessary, including the aforementioned additional improvement measures. Future research could focus on verifying the effectiveness of VR-based technical education in real-world settings, such as construction sites. This could involve conducting experiments with post-tensioning education subjects at actual construction sites to assess the impact of VR education on behavior and change in actual reality. In addition, future research could explore ways to improve the educational effectiveness of observing VR users by adding new interactions with surrounding observers and VR users, not just simple observations. This could involve developing and testing new educational methodologies that incorporate interactions between observers and VR users to enhance motivation and learning outcomes.

Bibliography

Adami, P., Rodrigues, P. B., Woods, P. J., Becerik-Gerber, B., Soibelman, L., Copur-Gencturk, Y., & Lucas, G. (2021). Effectiveness of VR-based training on improving construction workers' knowledge, skills, and safety behavior in robotic teleoperation. *Advanced Engineering Informatics*, *50*, 101431. https://doi.org/10.1016/j.aei.2021.101431

Almamlook, R., Bzizi, M., Al-Kbisbeh, M., Ali, T., & Almajiri, E. (2020). Factors Affecting Labor Productivity in the Construction Industry. *American Journal of Environmental Science and Engineering*, *4*(2), 24. https://doi.org/10.11648/j.ajese.20200402.13

Annett, J., & Stanton, N. A. (2000). *Task Analysis*. CRC Press.

Beyer-Berjot, L., Berdah, S., Hashimoto, D. A., Darzi, A., & Aggarwal, R. (2016). A Virtual Reality Training Curriculum for Laparoscopic Colorectal Surgery. *Journal of Surgical Education*, *73*(6), 932–941. https://doi.org/10.1016/j.jsurg.2016.05.012

Bilau, A. A., Ajagbe, M. A., Kigbu, H. H., & Sholanke, A. B. (2015). *Review of Shortage of Skilled Craftsmen in Small and Medium Construction Firms in Nigeria*. http://repository.futminna.edu.ng:8080/jspui/handle/123456789/10595

Boadu, E. F., Wang, C. C., & Sunindijo, R. Y. (2020). Characteristics of the Construction Industry in Developing Countries and Its Implications for Health and Safety: An Exploratory Study in Ghana. *International Journal of Environmental Research and Public Health*, *17*(11), Article 11. https://doi.org/10.3390/ijerph17114110

Carruth, D. W. (2017). Virtual reality for education and workforce training. *2017 15th International Conference on Emerging ELearning Technologies and Applications (ICETA)*, 1–6. https://doi.org/10.1109/ICETA.2017.8102472

Concannon, B. J., Esmail, S., & Roduta Roberts, M. (2019). Head-Mounted Display Virtual Reality in Post-secondary Education and Skill Training. *Frontiers in Education*, *4*. https://www.frontiersin.org/articles/10.3389/feduc.2019.00080

Crandall, B., Klein, G. A., & Hoffman, R. R. (2006). *Working Minds: A Practitioner's Guide to Cognitive Task Analysis*. MIT Press.

Crystal, A., & Ellington, B. (2004). Task analysis and human-computer interaction: Approaches, techniques, and levels of analysis. *New York*.

Cyma-Wejchenig, M., Tarnas, J., Marciniak, K., & Stemplewski, R. (2020). The Influence of Proprioceptive Training with the Use of Virtual Reality on Postural Stability of Workers Working at Height. *Sensors*, *20*(13), Article 13. https://doi.org/10.3390/s20133731

Demirel, D., Butler, K. L., Halic, T., Sankaranarayanan, G., Spindler, D., Cao, C., Petrusa, E., Molina, M., Jones, D. B., De, S., & deMoya, M. A. (2016). A hierarchical task analysis of cricothyroidotomy procedure for a virtual airway skills trainer simulator. *The American Journal of Surgery*, *212*(3), 475–484. https://doi.org/10.1016/j.amjsurg.2015.08.029

Detsimas, N., Coffey, V., Sadiqi, Z., & Li, M. (2016). Workplace training and generic and technical skill development in the Australian construction industry. *Journal of Management Development*, *35*(4), 486–504. https://doi.org/10.1108/JMD-05-2015-0073

Dubois, C.-A., & Singh, D. (2009). From staff-mix to skill-mix and beyond: Towards a systemic approach to health workforce management. *Human Resources for Health*, *7*(1), 87. https://doi.org/10.1186/1478-4491-7-87

Elnaga, D. A., & Imran, A. (2013). The Effect of Training on Employee Performance. *European Journal of Business and Management*.

Evans, K., Hodkinson, P., Rainbird, H., & Unwin, L. (2007). *Improving Workplace Learning*. Routledge.

Farmer, E. (1999). *Handbook of Simulator-based Training*. Ashgate.

Farra, S., Miller, E., Timm, N., & Schafer, J. (2013). Improved Training for Disasters Using 3-D Virtual Reality Simulation. *Western Journal of Nursing Research*, *35*(5), 655–671. https://doi.org/10.1177/0193945912471735

Feng, Z., González, V. A., Amor, R., Spearpoint, M., Thomas, J., Sacks, R., Lovreglio, R., & Cabrera-Guerrero, G. (2020). An immersive virtual reality serious game to enhance earthquake behavioral responses and post-earthquake evacuation preparedness in buildings. *Advanced Engineering Informatics*, *45*, 101118. https://doi.org/10.1016/j.aei.2020.101118

Fouskas, K. G., Pateli, A. G., & Spinellis, D. D. (2002). *Applying Contextual Inquiry for Capturing End-Users Behaviour Requirements for Mobile Exhibition Services*.

Gabbard, J. L., Hix, D., & Swan, J. E. (1999). User-centered design and evaluation of virtual environments. *IEEE Computer Graphics and Applications*, *19*(6), 51–59. https://doi.org/10.1109/38.799740

Golovina, O., Kazanci, C., Teizer, J., & König, M. (2019). Using Serious Games in Virtual Reality for Automated Close Call and Contact Collision Analysis in Construction Safety. *ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction*, *36*, 967–974. https://doi.org/10.22260/ISARC2019/0129

Grantcharov, T. P., & Reznick, R. K. (2008). Teaching Rounds: Teaching procedural skills. *BMJ : British Medical Journal*, *336*(7653), 1129. https://doi.org/10.1136/bmj.39517.686956.47

Hanna, A. S., Chang, C.-K., Sullivan, K. T., & Lackney, J. A. (2008). Impact of Shift Work on Labor Productivity for Labor Intensive Contractor. *Journal of Construction Engineering and Management*, *134*(3), 197–204. https://doi.org/10.1061/(ASCE)0733-9364(2008)134:3(197)

Jan, Z., Ahamed, F., Mayer, W., Patel, N., Grossmann, G., Stumptner, M., & Kuusk, A. (2023).

Artificial intelligence for industry 4.0: Systematic review of applications, challenges, and opportunities. *Expert Systems with Applications*, *216*, 119456. https://doi.org/10.1016/j.eswa.2022.119456

Kim, N., Anderson, B. A., & Ahn, C. R. (2021). Reducing Risk Habituation to Struck-By Hazards in a Road Construction Environment Using Virtual Reality Behavioral Intervention. *Journal of Construction Engineering and Management*, *147*(11), 04021157. https://doi.org/10.1061/(ASCE)CO.1943-7862.0002187

Kirkpatrick, D. L. (1998). The Four Levels of Evaluation. In S. M. Brown & C. J. Seidner (Eds.), *Evaluating Corporate Training: Models and Issues* (pp. 95–112). Springer Netherlands. https://doi.org/10.1007/978-94-011-4850-4_5

Kirwan, B., & Ainsworth, L. K. (1992). *A Guide To Task Analysis: The Task Analysis Working Group*. CRC Press.

Laberge, M., MacEachen, E., & Calvet, B. (2014). Why are occupational health and safety training approaches not effective? Understanding young worker learning processes using an ergonomic lens. *Safety Science*, *68*, 250–257. https://doi.org/10.1016/j.ssci.2014.04.012

Leder, J., Horlitz, T., Puschmann, P., Wittstock, V., & Schütz, A. (2019). Comparing immersive virtual reality and powerpoint as methods for delivering safety training: Impacts on risk perception, learning, and decision making. *Safety Science*, *111*, 271–286. https://doi.org/10.1016/j.ssci.2018.07.021

Lin, Y.-J., & Wang, H. (2021). Using virtual reality to facilitate learners' creative self-efficacy and intrinsic motivation in an EFL classroom. *Education and Information Technologies*, *26*(4), 4487–4505. https://doi.org/10.1007/s10639-021-10472-9

Makransky, G., Borre-Gude, S., & Mayer, R. E. (2019). Motivational and cognitive benefits of training in immersive virtual reality based on multiple assessments. *Journal of Computer Assisted Learning*, *35*(6), 691–707. https://doi.org/10.1111/jcal.12375

McAuley, E., Duncan, T., & Tammen, V. V. (1989). Psychometric Properties of the Intrinsic Motivation Inventory in a Competitive Sport Setting: A Confirmatory Factor Analysis. *Research Quarterly for Exercise and Sport*, *60*(1), 48–58. https://doi.org/10.1080/02701367.1989.10607413

Mechlih, H. (2016). New employee education using 3D virtual manufacturing. *2016 13th Learning and Technology Conference (L&T)*, 1–3. https://doi.org/10.1109/LT.2016.7562862

Mulder, M. (2014). Conceptions of Professional Competence. In S. Billett, C. Harteis, & H. Gruber (Eds.), *International Handbook of Research in Professional and Practice-based Learning* (pp. 107–137). Springer Netherlands. https://doi.org/10.1007/978-94-017-8902-8_5

Okoye, P. U., Mbakwe, C. C., & Igbo, E. N. (2018). Modeling the Construction Sector and Oil Prices toward the Growth of the Nigerian Economy: An Econometric Approach. *Economies*, *6*(1), Article 1. https://doi.org/10.3390/economies6010016

Osti, F., de Amicis, R., Sanchez, C. A., Tilt, A. B., Prather, E., & Liverani, A. (2021). A VR training system for learning and skills development for construction workers. *Virtual Reality*, *25*(2), 523–538. https://doi.org/10.1007/s10055-020-00470-6

Palter, V. N., & Grantcharov, T. P. (2010). Virtual Reality in Surgical Skills Training. *Surgical Clinics of North America*, *90*(3), 605–617. https://doi.org/10.1016/j.suc.2010.02.005

Parong, J., & Mayer, R. E. (2018). Learning science in immersive virtual reality. Journal of Educational Psychology, 110(6), 785.

Park, S. H., & Kang, T. H.-K. (2020). Data-Based Post-Tensioning System Controlled with Application in Internet of Things. *Proceedings of the Korea Concrete Institute*, *Vol.32 No.1*, 187–189.

Park, S., & Kang, T. H.-K. (2020). Smart Prestressing System in the Post-Tension Method: Algorithms for Data Analysis and Implementation in Internet of Things. 한국콘크리트학회 학술대회 논문집, *32*(2), 189–190.

Pittman, C., & LaViola, J. J. (2020). PhyAR: Determining the Utility of Augmented Reality for Physics Education in the Classroom. *2020 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, 760–761. https://doi.org/10.1109/VRW50115.2020.00231

Sacks, R., Perlman, A., & Barak, R. (2013). Construction safety training using immersive virtual reality. *Construction Management and Economics*, *31*(9), 1005–1017. https://doi.org/10.1080/01446193.2013.828844

Schraagen, J. M., Chipman, S. F., & Shalin, V. L. (2000). *Cognitive Task Analysis*. Psychology Press.

Shin, H., & Kang, T. H.-K. (2018). Effects of Individual Strand Force Deviation on Internal Pressure Capacity of PT Silos. 한국콘크리트학회 학술대회 논문집, *30*(2), 99–100.

Smith, S., & Ericson, E. (2009). Using immersive game-based virtual reality to teach fire-safety skills to children. *Virtual Reality*, *13*(2), 87–99. https://doi.org/10.1007/s10055-009-0113-6

Tang, X., & Yamada, H. (2011). Tele-operation Construction Robot Control System with Virtual Reality Technology. *Procedia Engineering*, *15*, 1071–1076. https://doi.org/10.1016/j.proeng.2011.08.198

Ward, P., Williams, A. M., & Hancock, P. A. (2006). Simulation for Performance and Training. In *The Cambridge handbook of expertise and expert performance* (pp. 243–262). Cambridge University Press. https://doi.org/10.1017/CBO9780511816796.014

Xi, N., Chen, J., Gama, F., Riar, M., & Hamari, J. (2023). The challenges of entering the metaverse: An experiment on the effect of extended reality on workload. *Information Systems Frontiers*, *25*(2), 659–680. https://doi.org/10.1007/s10796-022-10244-x

Zhao, D., & Lucas, J. (2015). Virtual reality simulation for construction safety promotion. *International Journal of Injury Control and Safety Promotion*, *22*(1), 57–67. https://doi.org/10.1080/17457300.2013.861853

Appendices

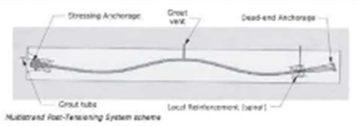
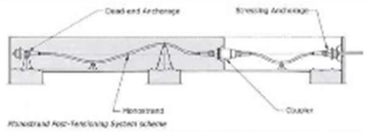
Appendix A. Text-based post-tensioning manual

SNUCEM Seoul National University Construction Engineering & Management	포스트텐셔닝 인장 작업 교육을 위한 서면 자료

여러분들은 지금부터 포스트텐셔닝 공법에서, 실제 결과물의 성능에 가장 큰 영향을 주는 스트레싱 작업에 대한 교육을 진행하게 됩니다. 본 교육자료는 Post-Tensioning Institute와 VSL의 포스트텐셔닝교육을 위한 자료를 기반으로 제작되었으며, 연구적인 목적으로만 사용됩니다.

1. Post-tensioning Work

포스트텐셔닝 작업은 **콘크리트 구조물의 강도를 향상시키고 지지력을 제공**하기 위해 적용되며, 이를 통해 종종 다른 건설 방법으로는 해결하기 어려운 설계 및 건설 과제를 해결할 수 있다. Bonded post-tensioning system 과 Unbonded Post-tensioning system으로 구별된다.

Bonded post-tensioning system	Unbonded Post-tensioning system
▪ 여러개의 스트랜드 (멀티스트랜드)로 구성된 텐던을 사용 ▪ 텐던이 가압되면 시멘트 혼합 그라우트가 덕트로 주입되어 주변 콘크리트와 접착 ▪ 주로 교량 및 교통 구조물의 새로운 건설에 널리 사용되며, 상업용 건물 구조에도 적용 ▪ 대형 구조 요소에 사용될 때 구간 길이와 하중 수용 능력의 증가, 굴곡의 감소와 같은 설계적 이점을 제공	▪ 단일 스트랜드로 구성된 텐던(Tendon)을 사용 ▪ 주변 콘크리트와 접착되지 않아 다른 구조체에 비해 지역적으로 움직일 수 있는 자유도가 있음 ▪ 주로 고가 슬래브, 지면 슬래브, 보 등의 건설에 사용 ▪ 가벼우면서도 유연하며, 쉽고 빠르게 설치될 수 있는 경제적인 솔루션
 Multistrand Post-Tensioning System scheme	 Monostrand Post-Tensioning System scheme
	

2. Unbonded Post-tensioning Work Procedure

[건설현장 포스트텐션 작업 단계]

1. 앵커리지, 덕트, 그리고 로컬 앵커리지 구역 보강(Local anchorage-zone reinforcement)
2. 스트랜드 스레딩
3. **<u>텐던 스트레싱</u>**
4. 앵커리지 캐핑

4단계의 과정 중, 포스트텐셔닝 작업에서 실제로 유압 기기를 작동하여 사고의 발생 위험이 높고, 인장에 따라 결과물의 성능에 영향을 줄 수 있는 **<u>3. 텐던 스트레싱</u>** 작업에 대한 세부 교육을 진행한다.

Seoul National University, Construction Engineering Management Lab.

3. Tendon Stressing

텐던은 일반적으로 강철 케이블 또는 스트랜드로 이루어진 긴 철사 또는 섬유를 뜻하며, 텐던은 일반적으로 콘크리트 구조물과 연결된 앵커에 고정된다. 스트레스를 가하기 위해 압축 펌프를 활용해 텐던에 인장력을 가함으로써 텐던과 연결된 스트랜드를 긴장한다. 이렇게 긴장된 스트랜드는 콘크리트 구조물 내에서 압축력을 생성하고, 구조물을 보다 강하고 안정적으로 만들어 준다. 따라서, 포스트텐셔닝 작업에서 텐던에 스트레스를 가해 주는 작업은 특히 중요한 역할을 한다.

[텐던 스트레싱 작업 수행을 위한 조건]

- 콘크리트가 데이터 시트에 명시된 **<u>최소 규정 강도(주로 3000psi)에 도달</u>**
- 콘크리트에 결함이 발생한 경우, 엔지니어의 승인 하에 필요한 강도를 달성할 수 있는 **<u>적합한 재료로 공극 보수 후</u>**에 작업 가능
- 거푸집이 앵커리지로부터 제거된 상태
- **<u>칼슘 염화물이나 칼슘 염화물을 함유하는 혼화제는 보수 작업에 사용해서는 안 됨</u>**

[텐던 스트레싱 작업 단계]

1. **앵커 헤드와 웨지 배치:** 이 작업은 콘크리트가 부어진 후에 수행되며, 앵커리지나 웨지의 표면이 콘크리트 산화물로 오염되지 않도록 해야 함
2. **잭 위치 조정**
3. **스트레싱:** 스트레싱 중에는 압력계에 표시된 압력과 텐던의 측정된 인장 길이를 기록
4. **하중 전달:** 잭의 압력을 풀어서 하중을 잭에서 앵커리지로 전달
5. **스트랜드 절단:** 스트레싱 작업이 완료되고 승인된 후에 초과 길이의 스트랜드 절단

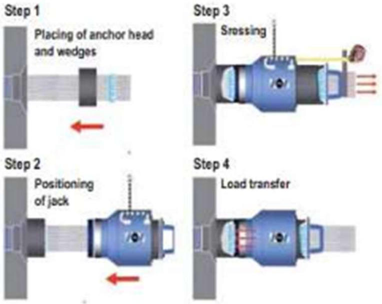
텐던 스트레싱 작업을 위해서는 유압 잭과 유압 펌프를 사용하여 각각의 텐던에 응력을 가한다. 해당 Unbonded post-tensioning 장비들은 현장에서 작업자가 이동시킬 수 있을 정도의 크기이며, 정해진 인장 길이를 모든 스트랜드에 달성함으로써 콘크리트 슬래브가 사전 설계된 강도에 도달할 수 있다. 유압 잭과 게이지는 각각 알려진 표준에 따라 최대 6개월 간격으로 캘리브레이션 해야 하며, 각 잭과 게이지에 대한 결과 인증서를 제공해야 한다.

실제 현장에서의 인장 작업

텐던은 구조물의 중요한 구성 요소로 작용하여 균열과 변형을 방지한다. 그러나 올바르게 인장된 텐던과 잘못 인장된 텐던은 외관상으로 구별하기 어렵기 때문에 올바른 인장 결과를 보장하기 위해 경험이 있는 훈련받은 작업자와 검사관의 참석이 필요하다.

[텐던 스트레싱 작업의 위험성과 안전수칙]

- 스트레싱 작업은 구조물에 높은 압력을 가하는 과정으로, 적절한 안전 절차를 따르지 않으면 작업자에게 높은 위험을 초래할 수 있음
- 장비를 작동시키고 측정하는 사람은 **실제 압력을 받는 텐던 뒤에 서서는 안 됨**
  → 텐던이 파괴될 수 있고 클램프가 풀릴 수 있으며 순간적으로 큰 힘이 방출되어 텐던이 파단되거나 고정 장치에서 벗어날 수 있기 때문이며, 이는 작업자의 생명과도 직결될 수 있는 사고 발생 가능성을 가짐
- 프로젝트의 모든 참여자가 텐던이 인장 작업 중에 있음을 알 수 있도록 경고 시스템 등의 **위험 요소 식별을 위한 대비책**을 마련해야 함
- 스트레스를 가하는 동안 작업자는 텐던 및 유압 장비와 충돌하지 않도록 해야 하며, 스트레스 작업이 진행되는 구역은 출입 제한
- 작업자는 보호 장갑과 안전 모자를 착용해야 함



[스트레싱 작업시 주의사항 및 품질관리]

- 스트레싱 작업을 시작하기 전에 **정확한 위치를 표시**하고 작업을 수행
- 텐던의 스트레싱 작업 시 충격을 피하기 위해 **부드럽게 스트레스를 가함**
- 텐던 스트레싱 작업 중에는 텐던의 오염, 파손, 잘못된 앵커 설치, 그리고 텐던에 과도한 스트레스 발생 등의 결함 방지
- 스트레싱을 통해 공극이나 기타 콘크리트 결함(ex. 베어링 플레이트가 콘크리트 안으로 침입하는 경우)가 발견된 경우, 즉시 장비에서 압력을 완전히 풀고 결함이 있는 콘크리트를 제거해야 함
- 압력을 가할 때 뿐만 아니라 유압 장비를 사용해 압력을 **감소시킬 때에도 주의**를 기울여야 하며, 유압장치의 압력 생성 내부 구조에 압력이 쌓여 실린더에 손상이 발생하지 않도록 주의
- 스트레스된 부재의 **품질 관리를 위해서 앵커의 접속 강도 테스트, 텐던의 인장강도 검사** 등이 이루어짐
- 텐던 스트레싱 작업을 완료한 후에 재긴장을 할 시 웨지 되물림 등으로 인한 파단 가능성이 있기 때문에 **추가적인 스트레스를 가해서는 안 됨**

[텐던 스트레싱 작업 후 신장량 측정과 검토 과정]

텐던 스트레싱 작업이 완료되면 신장량 측정이 이루어진다. 신장량 측정은 텐던에 적용된 스트레스의 정확성을 확인하기 위해 수행된다. 만약 측정된 신장량과 설계된 신장량의 차이가 ±7%의 오차 범위를 벗어날 경우, 다음과 같은 과정을 통해 이를 검토해야 한다.

1. 다른 텐던 검사: 동일한 부재에서 다른 텐던들을 검사하여 동일한 오차가 있는지 확인

다른 텐던의 측정값과 설계된 연신률을 비교하여 일관성이 있는지 확인한다. 모든 텐던에서 비슷한 오차가 나타난다면, 시스템 전반에 영향을 미치는 요인이 있는 것으로 볼 수 있다.

2. 신뢰성 확인: 신장량을 측정하는 방법과 장비의 정확성을 다시 확인

올바른 도구와 적절한 방법을 사용하여 측정이 정확히 이루어졌는지 확인한다. 이 때, 스트레싱 작업에 필요한 모든 부속품이 장비에 장착되어 있는지 확인하고, 필요한 경우 측정 장비를 교정하거나 대체한다.

3. 추가 검토: 설계 및 시공에 참여한 기술자나 전문가와 상의하여 문제를 검토하고 해결책 모색

설계 상의 오차나 시공 과정에서의 문제 등을 확인하고 수정할 수 있다. 필요한 경우 측정된 신장량을 보정하는 작업을 수행하거나, 추가적인 계산이나 보정 공식을 사용하여 신장량을 수정할 수 있습니다. 이를 통해 설계된 신장량과 더 가까운 값을 얻을 수 있다.

작업자는 작업 완료 시 텐던 스트레싱 장비를 안전하게 해제해야 하며, 작업이 완료된 후에는 작업 기록을 검토하고, 이상 사항이 있는 경우에 한하여 라이선스를 보유한 설계 전문가에게 승인을 받아야 한다.

Appendix B. Quiz

SNUCEM Seoul National University Construction Engineering & Management | 포스트텐셔닝 인장 작업 교육 성과 확인 퀴즈

포스트텐셔닝 교육의 성과를 평가하기 위한 퀴즈입니다. 총 20문항이며, 모든 문제에는 복수정답이 있을 수 있습니다. 본 퀴즈의 제한시간은 10분입니다.

1. 텐던 스트레싱 작업을 시작하기 전에 사전에 해야 하는 작업에 대해 고르시오.
a) 스트레싱을 수행할 장비의 정확한 강도를 계산한다.
b) 계획된 스트레싱 위치를 표시한다.
c) 앵커리지 캐핑 작업을 한다.
d) 텐던을 정확하게 청소하고 윤활 작업을 한다.

2. 텐던 스트레싱을 진행 과정 중 올바른 것을 선택하시오.
a) 충격을 피하기 위해 텐던을 부드럽게 스트레싱한다.
b) 텐던 스트레싱 작업을 완료한 후에는 추가적인 스트레스를 가하지 않아야 한다.
c) 스트레싱 작업을 수행할 때는 안전 모자를 착용해야 한다.
d) 스트레스 측정 시에는 마찰 계수를 무시하고 진행한다.

3. 텐던 스트레싱 작업 후에 확인해야 하는 것을 고르시오.
a) 계산된 신장량과 측정된 신장량의 일치 여부를 확인한다.
b) 텐던의 길이와 직경을 다시 측정하여 정확성을 검토한다.
c) 스트레싱 작업 중 발생한 결함이 있는지 확인한다.
d) 스트레싱 작업에 사용된 장비의 교정 인증서를 검토한다.

4. 텐던 스트레싱 작업 중에 다음 중 주의해야 할 사항은 무엇인가?
a) 작업자는 텐던과 장비 사이에서 안전 거리를 유지해야 한다.
b) 스트레싱 작업이 진행되는 구역에서는 출입을 제한해야 한다.
c) 텐던 스트레스 측정 시에는 압력 누출을 방지하기 위해 정기적인 윤활이 필요한다.
d) 작업자는 스트레싱 작업 전에 사용 장비의 상태를 점검하지 않아도 된다.

5. 텐던 스트레싱 작업에 사용되는 장비를 검사할 때 다음 중 무엇을 확인해야 하는가?
a) 장비가 올바르게 교정되었는지 확인한다.
b) 스트레싱 작업에 필요한 모든 부속품이 장비에 장착되어 있는지 확인한다.
c) 스트레싱 작업 중에 발생할 수 있는 위험 요소를 식별하고 대비책을 마련한다.
d) 스트레싱 작업 전에 작업자가 필요한 안전 장비를 착용했는지 확인한다.

6. 포스트 텐션 시공 과정에서 텐던 스트레싱 작업은 주로 어떤 시점에 수행되는가?
a) 콘크리트가 충분한 강도에 도달한 후에 수행된다.
b) 텐던 설치가 완료된 후에 수행된다.
c) 철근 배치가 완료된 후에 수행된다.
d) 콘크리트 교체 작업 전에 수행된다.

Seoul National University, Construction Engineering Management Lab.

7. 텐던 스트레싱 작업 중에 작업자의 부상과 직결될 수 있는 가장 중요한 안전사항은 무엇인가?
a) 작업자의 안전 모자 착용
b) 작업 현장의 출입 제한
c) 스트레싱 작업 중 작업자 간의 원활한 의사소통
d) 작업자가 스트레싱 장비 뒤에 서지 않는 것

8. 텐던 스트레싱 작업 시에는 스트레스를 어떻게 적용해야 하는가?
a) 일정한 속도와 압력으로 부드럽게 적용한다.
b) 갑작스런 충격을 줘서 스트레스를 적용한다.
c) 최대한 빠르게 스트레스를 적용한다.
d) 스트레싱 속도에 따라 작업자의 판단에 따라 다르게 적용한다.

9. 텐던 스트레싱 작업 후에 어떤 검사를 수행해야 하는가?
a) 텐던 스트레스를 다시 검증한다.
b) 콘크리트의 강도를 다시 측정한다.
c) 스트레싱 작업 중 발생한 결함을 확인한다.
d) 스트레싱 작업에 사용된 장비의 보수 기록을 확인한다.

10. 텐던 스트레싱 작업에서 사용되는 스트레스를 조절하는 장비는 어떤 것들이 있는가?
a) 유압식 스트레싱 잭
b) 유압 펌프
c) 윈치
d) 덕트

11. 텐던 스트레싱 작업에서 발생할 수 있는 결함으로 옳은 것은 무엇인가?
a) 텐던의 오염
b) 텐던의 파손
c) 잘못된 앵커 설치
d) 텐던의 과도한 스트레스

12. 텐던 스트레싱 작업 시 작업자의 안전을 위해 취해야 하는 조치로 옳은 것은 무엇인가?
a) 작업자 간의 소통 및 신호 체계 확립
b) 안전모 및 안전고글 착용
c) 스트레싱 작업 시 작업자의 위치 확인
d) 작업 중에는 보호 장갑 착용

13. 텐던 스트레싱 작업 시 품질 관리를 위해 어떤 검사나 점검이 이루어져야 하는가?
a) 신장량 측정
b) 앵커의 접속 강도 테스트
c) 텐던의 인장강도 검사
d) 스트레스 장비의 교정

14. 텐던 스트레싱 작업 중 텐던에 적용되는 스트레스는 어떻게 측정되는가?
a) 압력 게이지 판독
b) 신장량 측정
c) 모멘트 측정
d) 진동 센서 사용

15. 텐던 스트레싱 작업 시 텐던에 적용되는 스트레스를 조절하기 위해 사용되는 장비는 무엇인가?
a) 잭
b) 풀리
c) 윈치
d) 압력 게이지

16. 스트레싱 작업을 위해 필요한 조건은 무엇인가?
a) 콘크리트에 결함이 없을 것
b) 콘크리트의 강도가 데이터 시트에 명시된 최소 규정 강도에 도달할 것
c) 칼슘 염화물을 함유하는 혼화제 사용
d) 거푸집이 앵커리지로부터 제거된 상태

17. 포스트텐셔닝 작업의 목적은 무엇인가?
a) 콘크리트 구조물의 강도 향상과 지지력 제공
b) 콘크리트 구조물의 무게 감소
c) 건물 외관의 개선
d) 건설 비용의 절감

18. 포스트 텐션 작업 시, 다음 중 측정된 신장량과 계산된 신장량의 차이가 +/-7% 범위를 초과할 경우 취해야 하는 조치가 아닌 것은?
a) 신장량을 다시 측정하여 정확성을 확인한다.
b) 텐던에 추가적인 스트레스를 가하여 신장량을 조정한다.
c) 엔지니어의 승인을 받아 문제를 해결한다.
d) 장비를 교정하거나 대체하여 정확성을 개선한다.

19. 포스트 텐션 작업 시, 다음 중 안전을 위해 주의해야 할 사항으로 옳은 것은 무엇인가?
a) 스트레스를 가하는 동안 작업자는 텐던 장비와 충돌하지 않도록 한다.
b) 스트레스 작업이 진행되는 구역에서는 출입을 제한한다.
c) 작업자는 보호 장갑과 안전 모자를 착용해야 한다.
d) 유압 장비가 작동되는 중에 작업자는 자유롭게 위치하여 신장량을 체크한다.

20. 포스트 텐션 작업 시, 다음 중 스트레싱 작업 후의 안전 절차는 무엇인가?
a) 스트레스가 완료된 후에는 측정된 신장량과 계산된 신장량을 비교하여 일치하는지 확인한다.
b) 작업자는 작업장을 철거하기 전에 텐던 장비를 안전하게 해제한다.
c) 작업이 완료된 후에는 텐던에 추가적인 스트레스를 가하지 않아야 한다.
d) 스트레스가 완료된 후에는 작업 기록을 검토하고 라이선스를 보유한 설계 전문가에게 반드시 승인을 받아야 한다.

Appendix C. Intrinsic Motivation Inventory Survey

SNUCEM Seoul National University Construction Engineering & Management

Intrinsic Motivation Inventory survey on Tensile Work Training of Post-tensioning Construction

본 설문에 참여해 주셔서 정말 감사드립니다. 이 설문은 여러분의 포스트텐셔닝 교육 도중 느꼈던 생각들에 대한 응답을 기록하기 위한 설문입니다. 해당 설문은 1: 전혀 그렇지 않다에서, 7: 매우 그렇다 까지 총 7개의 척도로 구성되어 있습니다. 모든 질문에 응답을 해 주셔야 하며, 하나의 질문에는 하나의 척도만 선택하실 수 있습니다.

전혀 그렇지 않다 .... 보통 이다 .... 매우 그렇다

No.	항목 내용	1	2	3	4	5	6	7
1	해당 교육이 즐겁다고 생각했다.							
2	포스트텐셔닝 교육을 잘 받으려고 노력하지 않았다.							
3	나는 포스트텐셔닝 인장 작업을 숙달했다고 생각한다.							
4	해당 교육은 나에게 가치가 있다고 생각한다.							
5	본 교육은 지루한 활동이었다.							
6	본 인장 작업 교육을 통해 나는 어떠한 이점을 얻을 수 있다고 생각한다.							
7	나는 포스트텐셔닝 작업에 대한 지식 습득 정도에 만족한다.							
8	해당 교육을 받으며 불안감을 느꼈다.							
9	포스트텐셔닝 교육에서 개념을 이해하는 데 어려움을 겪었다.							
10	교육을 받는 동안 많은 에너지를 투자하지 않았다.							
11	해당 교육을 다른 사람에게 추천할 의사가 있다.							
12	다른 참가자들과 비교했을 때, 나의 포스트텐셔닝 교육에 대한 이해도가 더 높다고 생각한다.							
13	포스트텐셔닝 작업을 충분히 이해하기 위해 많은 노력을 기울였다.							
14	포스트텐셔닝 작업교육은 나의 관심을 끌지 못했다.							
15	본 작업 교육을 진행하면서 압박을 받았다.							
16	해당 교육을 통해 포스트텐셔닝 작업에 대한 이해도가 높아졌다고 생각한다.							
17	나는 포스트텐셔닝 교육을 잘 이수하는 것이 중요하다고 생각했다.							
18	해당 교육이 포스트텐셔닝 인장 작업 이해를 위해 중요하다고 생각한다.							
19	해당 교육이 흥미롭다고 생각했다.							
20	교육을 받는 과정에서전혀 긴장하지 않았다.							
21	본 포스트텐셔닝 인장 작업 교육을 통해 얻은 지식이 유용하다고 생각한다.							
22	포스트텐셔닝 인장 작업에 대하여 잘 알게 되었다.							
23	해당 교육을 진행하면서 매우 편안했다.							
24	본 교육을 이수한 것은 나의 발전에 도움이 되는 활동이었다.							

Seoul National University, Construction Engineering Management Lab.

국 문 초 록

가상현실(VR)과 같은 신기술의 등장으로 효과적인 교육 프로그램들이 개발되고 있지만, 해당 기술들은 건설산업에 널리 보급되어 있지 않거나 건설 현장에서 낮은 활용성을 보인다. 본 연구는 건설 산업에서의 기술 교육을 위해 계층적 작업 분석(HTA)을 기반으로 하는 종합적인 프레임워크를 중심으로 VR 기반 포스트텐셔닝 인장 작업 교육 프로그램을 개발하였다. 이를 위해 작업 단계와 구현 목표 분석을 통해 교육 프로그램을 설계하고, VR 환경 구현에 필수적인 기능을 도출하였다. 교육 성능을 평가하기 위해 본 연구에서 개발한 VR 기반 교육을 받은 학생들과 기존 교육 방법을 통해 학습한 학생들의 학습 효과를 비교하여 VR 교육 프로그램의 효과를 검증하였다. 또한, VR 교육의 공간적 제약을 극복하고 많은 사용자에게 교육 효과를 줄 수 있는 VR 사용자 관찰 학습 방식이라는 새로운 방법론을 제안하여 해당 교육 방법의 성능을 평가하였다. 연구 결과는 VR을 기반으로 한 기술 교육 프로그램이 향상된 학습 성과를 보이는 것을 확인하였으며, 본 연구에서 제시하는 종합적인 프레임워크가 건설 산업 기술 교육에서 기존 교육 방법의 문제점을 극복할 수 있는 잠재력을 가지고 있음을 시사한다.

주요어: 가상현실 기반 훈련; 포스트텐셔닝; 계층적 과업 분석; 가상 환경; 훈련 시나리오 개발

학 번: 2021-22662