



HAL
open science

Co-design and evaluation with construction workers of virtual reality and force feedback modalities for formwork panel action training

Mehdi Hafsia, Eric Monacelli, Laure Ducoulombier

► To cite this version:

Mehdi Hafsia, Eric Monacelli, Laure Ducoulombier. Co-design and evaluation with construction workers of virtual reality and force feedback modalities for formwork panel action training. *Cognition, Technology and Work*, 2026, <10.1007/s10111-025-00853-2>. <hal-05503094>

HAL Id: hal-05503094

<https://hal.science/hal-05503094v1>

Submitted on 24 Mar 2026

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons CC BY 4.0 - Attribution - International License



Co-design and evaluation with construction workers of virtual reality and force feedback modalities for formwork panel action training

Mehdi Hafsia¹ · Eric Monacelli¹ · Laure Ducoulombier²

Received: 24 July 2022 / Accepted: 19 December 2025
© The Author(s) 2026

Abstract

Construction is one of the sectors most at risk in terms of health and safety. The social security system attributes more than 14% of the accidents recorded in 2018 to the construction sector. In addition to safety risks, construction workers are exposed to occupational diseases. Musculoskeletal disorders (MSD) are at the top list of the most frequent occupational diseases. In order to address these issues, construction companies have implemented health and safety policy to protect their employees. This policy provides, among other things, for an improvement in the organizational aspect of work, the adaptation of work to people and training. Training is carried out according to a classic methodology: theoretical and practical training. The training represents constraints of cost, duration and organization. The content must be adapted to specific profiles, be repeatable and allow the trainers to assess the level of the trainees. For training on the right actions and posture to avoid the risk of MSDs, the impact of virtual reality training is less relevant due to the lack of haptic feedback. In this article, we propose to evaluate with the construction workers a new training methodology based on visual immersion and a robotic platform for haptic interaction with motion tracking. This methodology is evaluated for a particular task: the formwork panel adjustment, a highly risky operation on a highly sensitive tool. We believe that this approach would allow to better engage the construction workers during training on the formwork, to ensure their safety and awareness of MSD risks. The objective through this method is to enable the construction workers to understand the risks linked to their job, to train them to avoid risks, and to enable the trainer to benefit from a tool for monitoring and supporting the construction workers. In order to validate the methodology, experiments were conducted and questionnaires were submitted to two profiles of people: novices and professionals. This experimentation shows an acceptance of the solution by the construction workers.

Keywords Virtual reality · Force feedback · Posture analysis · Training · MSD · Construction · Co-design

1 Introduction

The French construction industry is of major economic importance. According to the report published by the French Construction Federation (Fédération Française du bâtiment 2020), construction activity exceeded 140 billion euros in 2019. It responds to major challenges such as the need for housing and population growth. The sector therefore has a constant need for a skilled workforce to meet these challenges.

Construction remains a high-risk industry for employees' health and safety. Indeed, in 2018, according to the statistics of the CNAM (French national health insurance fund) (CNAM 2020), the construction sector represents 14% of all work-related accidents recorded in the various industries, 16% of accidents leading to permanent disability and 19%

✉ Mehdi Hafsia
me.hafsia@gmail.com

Eric Monacelli
eric.monacelli@uvsq.fr

Laure Ducoulombier
Laure.ducoulombier@centralelille.fr

¹ LISV – UVSQ, Paris–Saclay University, 10–12 Avenue de l'Europe, 78140 Vélizy–Villacoublay, France

² Ecole Centrale de Lille, Cité Scientifique, 59650 Villeneuve-d'Ascq, France

to deaths. These accidents accumulated a little over six million lost work days for the sector. The same year, in terms of occupational diseases, the construction sector represents 15.3% of the statistics collected by the CNAM all sectors combined, 16% led to permanent disability and 19% to deaths due to an occupational disease. Occupational diseases have thus accumulated 1.6 million lost working days.

Any accident can potentially have a consequence. There are two families of risks to which employees are exposed: Immediate Risks (IR) and Deferred Risks (DR).

IR are risks whose damage occurs without exposure over a minimum period of time. For instance, when working at heights, there is a risk of falling, and in the event of an accident, the consequences will be immediate.

On the contrary, DR cause damage whose effects occur in the long term. In construction, one of the most present deferred risks is the development of Musculoskeletal Disorders (MSD). Bio-mechanical factors contribute strongly to the occurrence of MSDs. Indeed, manual handling is the primary cause of the appearance of these disorders. It was responsible for 48% of MSDs in 2018 (CNAM 2020).

This article outlines the results of a new methodology for training construction workers in order to avoid the appearance of musculoskeletal disorders (MSDs). MSDs and current training methods are discussed in order to situate our work in the state of the art. The rationale and main benefits for the use of virtual reality (VR) in posture training for the construction sector and the importance of haptic feedback in improving immersion were discussed with the construction workers. Significant research and projects carried out in this field are also presented, followed by the description of the experiment's protocol in order to validate the methodology. Finally, the results are discussed and a conclusion is drawn.

1.1 Musculoskeletal disorders

MusculoSkeletal Disorders (MSD) is a term for abnormalities affecting the lower and upper limbs as well as the spine of the human body. They are generally related to physical activities that place stress on the entire musculoskeletal system and are considered the leading cause of disability (Hales and Bernard 1996; Punnett and Wegman 2004).

These disorders affect the tissues that support the joints. They affect shoulders, back, wrists, knees, and ankles, manifesting as tendinitis or sciatica and are due to repeated stress on the joints during professional activity. These disorders are manifested by functional pain and may, at an advanced stage, generate more serious consequences that may prevent continued employment, such as temporary or permanent incapacity or disability at work (Punnett and Wegman 2004). MSDs occur mainly during prolonged and repeated handling of heavy objects in inappropriate postures. The

construction sector is one of the most sectors concerned by these disorders. Indeed, the industry is at risk due to the complexity of tasks, constraints related to planning, and complex working conditions. In addition, the French Professional Organization for Prevention in the Building and Public Works industry has identified that nine out of ten occupational diseases are due to MSDs, as cited in OPPBTP (2016). In addition, The HSE estimates that 65% of occupational diseases identified in the construction sector are due to MSDs (Health and Safety Executive 2017). Diagnosis is generally late. Indeed, the building and public works sector is a very "male" sector. Profiles, called "employee", are used to the harshness of the task, rarely complain and ignore the alarming signals and pains, associating them with the "risks of the job" (OPPBTP 2016).

The study of the organism also specifies that there are different factors of MSD which are: organizational, individual, aggravating and biomechanical.

From an organizational point of view, some situations on the job site can be complicated. employees are sometimes confronted with unsuitable equipment stock or remote storage areas. Tight turnaround times, the absence or failure of handling assistance equipment are also a source of MSDs. Vibrations transmitted by tools such as drills or jackhammers or by the driving of construction machinery increase this risk. Finally, physical conditions, age and time spent on difficult jobs reinforce the impact of these risks. On the job site, the body of the employee is sometimes put to the test. They find themselves in unusual work postures such as arms outstretched, kneeling or even bent backs. It is also possible that he may find himself in situations with objects grasping or to force himself during the tightening phase. Moreover, these actions can be repeated. Repetition of these movements leads to an increased risk of developing MSD (OPPBTP 2016).

To avoid these risks, the OPPBTP recommends certain actions (OPPBTP 2016). Indeed, these recommendations are addressed to employees and companies. For the employee, few rules exist. It is thus advisable not to squat or get up quickly, leaning on the arms so as not to let the knees support all the weight of the body. It is also advisable to make sure that the arms are at shoulder height when working at height. With regard to carrying loads, it is recommended for heavy loads to be carried by two employees and to adapt its posture when carrying and moving the load, when it is not possible to mechanize or reduce the weight at the source (OPPBTP 2016).

For companies, the OPPBTP suggests an appropriate action plan. For example, it is recommended to opt for vibration-reducing equipment and to invest in newer equipment. Financial assistance to fund the equipment or promote MSD prevention is also suggested. It is also important to

check the condition of the equipment being used and to maintain it properly. The use of personal protective equipment can also reduce risk by protecting operators from cold or shock. Finally, the OPPBTP advises informing employee of the risks involved. Indeed, companies are required to train their workers, according to the French Ministry of Labor (Ministère du Travail 2008). Training in actions and postures is therefore mandatory in order to inform the employee of the risks related to their jobs and thus prevent the appearance of occupational diseases and in particular MSDs.

1.2 Problematic

Training is defined by Beach (Beach 1965) as a process of acquiring knowledge and improving skills for a specific purpose.

There are four questions that must be answered when setting up a training program:

1. Who is it for?
2. What type of training should be set up?
3. For what purpose?
4. When should it take place?

On-the-job training is the process of acquiring the knowledge and skills necessary for the job. It can also be defined as the set of tools facilitating the learning of behaviors and skills that allow integration into the company. Across all sectors, training is a key step for all stakeholders, enabling employees to acquire, consolidate, or enhance their professional skills and knowledge of their trade. At the same time, it supports employers in ensuring that their workforce maintains a high level of expertise, complies with internal procedures and regulations, improves productivity, and consistently upholds health and safety standards, thereby contributing to overall organizational efficiency and risk prevention. Beyond the development of the employees' skills, and since the evolution of the French legislation concerning the professional training of the labor code (du

Travail 2019), the companies have set up training in health and safety prevention. This training thus allow to train the employees on the precautions to take to ensure their safety and that of their colleagues, the prevention measures to respect in the company and the behavior to adopt in case of accident. The objective is to make the workers aware of and able to control the risks specific to their environment and their workstation. The content is provided when a new employee arrives at a risky workstation or when a workstation is created or modified to expose them to new risks. In the report from the British HSE, the study also mentions occupational illnesses, which affect health during the work activity or afterwards (Health and Safety Executive 2017). For these reasons, in addition to the safety training provided, employees are also required to attend health-related training courses. These courses focus on learning how to prevent health-related risks (deferred risks). These training courses can deal with the psycho-social aspect of health, but also with actions, postures or work habits. While some health risks are visible and measurable, others, develop over years and are harder to detect. Among these risks, Musculoskeletal disorders (MSDs) are the most common diseases (Valero et al. 2016). Beyond prevention campaigns based on informative posters placed on the work sites, reminders of the rules during safety quarters, morning warm-ups, robotization and industrialization processes of the work sites, the sector is betting on training in order to better inform the employees on the postures and actions to be adopted during the accomplishment of the different daily tasks (Ganah and John 2015).

1.3 Current methods

Training is a must for all construction workers. Whether they are newcomers or experienced, they are all required to undergo a numerous training sessions throughout their career. This training has three main objectives: to increase skills, to raise awareness of the risks associated with the job and to learn the right actions and posture when performing specific tasks.

During the training, the construction worker is supervised by two key experts: a trainer and an ergonomist (Fig. 1). Although they work closely together, two distinct roles for each can be defined.

The trainer accompanies the trainee in the understanding of the task and the increase in competence. The trainer will also take care of the training and the risk awareness because of his experience on site.

The ergonomist intervenes during the tasks that involve manual handling of loads and anything that involves unusual positions and postures. His role is to make the trainees

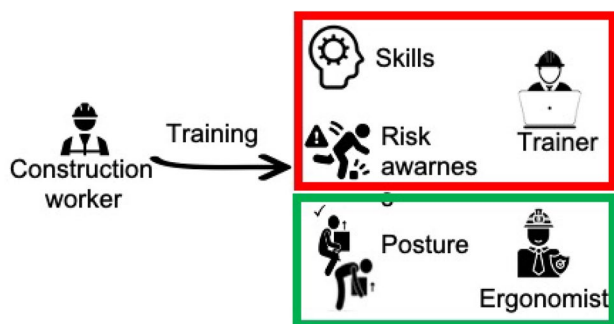


Fig. 1 Definition of the experts' roles and training objectives

aware of the need to adopt the right posture when handling heavy objects.

The training therefore allows:

- The trainee to increase his competence, to know the different processes related to his job, to know how to use the different tools and to be able to work in complete safety.
- The trainer to evaluate the performance of the trainees by observation and detect bad understanding or behavior
- The ergonomist to evaluate the trainees' awareness of the risks of their jobs and evaluate, for certain situations, the understanding of the risks related to the posture, in a qualitative way.

The industrial partner's ambition in terms of health and safety is to achieve zero risk-taking and zero accidents. This ambitious objective, which is supported by the entire company, is backed by a strong health and safety policy. The "safety" road map is broken down into five major points comprising a number of actions to be implemented. Among these points are the focus on HIPO (HIGH POTential risks) incidents, the consideration of safety at the contractual level for stakeholders, the reinforcement of the safety culture, the standardization and simplification of processes and finally the point to which this work is linked, the reduction of dangerous events. This last point is based on several actions, including innovation, whether it be at the material, organizational or training level. This "safety" road map is



(a) "K-Ryole" assistant cart



(b) Zero-G Arm

Fig. 2 Examples of innovations developed for the industrial partner

accompanied by a "health plan" which is based on four major areas: ergonomics and the reduction of arduousness, life balance, monitoring of the physiological and psychological state of employees and finally work organization. Concerning ergonomics and the reduction of arduousness, two points involve training and raising the awareness of decision-makers and players. Each entity must then take a position on the actions implemented with a follow-up of the performance and result indicators on these actions. The company innovates by implementing solutions for mechanizing handling. Indeed, several solutions are deployed in the field, such as exoskeletons, electric pallet trucks, the "K-Ryole" (Fig. 2a, K-Ryole (2020)), an electric assistance cart that can carry 250 kg of load effortlessly, or the Zero-G Arm, a fully mechanized anti-gravity arm that makes it easier to handle electric tools without having to bear the weight of them (Fig. 2b).

The company also relies on the various training courses that have been put in place, believing that employee training is an important step before sending them to the site. This training is aimed at a particular type of population: the employee. The training is provided by two organizations: the Gustave Eiffel Apprentice Training Center (CFA Gustave Eiffel,¹ which trains the younger generation of employees, and the MATFORM² center, which trains employees and temporary workers and also provides training in certain workshops for the CFA. Both organizations are affiliated with the technical and material base of the industrial partner. The training courses are formalized by the training centers at the request of the client: the construction site. The training centers set up a specific training program for a specific need in terms of operational manpower, taking into account the level of basic knowledge of the targeted trainees, and divided into two parts: a theoretical part and a practical part.

1.3.1 Theoretical session

The goal of any industrial company is to have skilled employees. This is based on training enhancing the employer brand. This involves equipping the management team with tools to communicate the company's vision on safety and innovation, attracting and retaining talent, aligning employees with company culture, and offering career advancement opportunities (Smith 2018).

Theoretical knowledge is crucial for understanding not just how to perform tasks, but also their role in the overall process (Jones 2019). In classical training sessions, trainees are guided by a trainer in a classroom setting using visual aids (Williams 2020).

¹ CFA Gustave Eiffel: www.centregustaveeiffel.fr

² MATFORM: www.bycn-matform.com

Trainers cover on-site situations (e.g., working at heights, using electrical equipment), discussing associated risks, equipment (e.g., harnesses), and authorizations (e.g., electrical permits) (Brown 2021). Trainees also learn to identify risks, handle emergencies, and ensure safety and compliance (Davis 2022).

During these sessions, learners are mostly passive and do not engage in physical activities. While this approach effectively transfers theoretical knowledge, it may not fully engage trainees in practical skill development (Miller 2023).

1.3.2 Practical session

Introducing new tools, processes, or methods requires a training campaign to explain changes, such as ergonomic improvements or compliance with standards. Practical training is essential because theoretical knowledge alone is insufficient for real-world application. Hands-on practice helps employees apply what they've learned in a field setting.

In practical sessions at the industrial partner's training base, trainees start with a safety review and muscle warm-up before using tools under a trainer's supervision, who ensures safety and proper use of personal protective equipment (PPE).

The success of these sessions depends on the trainer's expertise in balancing theory and practice. Research shows that practical training enhances skill retention and application (Smith and Brown 2021; Johnson et al. 2019). Trainees, often experienced manual workers, prefer hands-on learning. Trainers must integrate theoretical concepts with practical workshops to keep trainees engaged, although this can be challenging due to costs and feasibility. Practical sessions also carry risks, including potential injuries, making safety and supervision critical. New training formats are being developed to improve motivation, evaluation, and consistency in training.

1.3.3 Digital learning: new training methods

The introduction of new technologies has opened up new learning methods. Adapting training to digital media enhances engagement and learning experiences. Studies show that digital environments improve outcomes by catering to diverse learning styles and providing interactive experiences (Davis 2005; Garrison 2011).

Digital training overcomes traditional methods' limitations, such as fixed schedules and standard content. Digital environments allow personalized learning, with content accessible at one's own pace, promoting deeper learning through interactive elements (Garrison 2011). Online

simulations and virtual labs enable practical skills practice, bridging the gap between theory and application.

The rapid evolution of technology and industry practices makes traditional methods increasingly inadequate. Digital training supports continuous learning and adaptation to new technologies and processes (Pereira and Romero 2017; Hecklau et al. 2016). Formats like MOOCs and mobile learning applications enhance accessibility and engagement through interactive features and multimedia content (Papano 2012; Yousef et al. 2014).

Serious Games (SGs) and Virtual Reality (VR) technologies address traditional training limitations by offering interactive, more realistic scenarios for practice. SGs like "Risk Hunting" and VR environments provide immersive experiences that better reflect real-world conditions (Connolly et al. 2012; Sacks et al. 2013; Wang et al. 2018).

Overall, digital methods offer interactive, flexible, and engaging learning experiences, addressing conventional training's limitations by incorporating adaptive technologies and immersive environments. One key advantage is the ability to safely repeat tasks in a controlled setting, which enhances learning by doing, a core principle of experiential learning theory (Kolb 1984). This repetitive, hands-on approach ensures that learners not only acquire theoretical knowledge but also develop practical skills in a risk-free environment (Schön 1987). Moreover, immersive simulations allow for real-time feedback and adjustments, which has been shown to significantly improve retention and competency (Mayer 2005). As technology advances, leveraging these tools is crucial for effective and relevant training, ensuring both safety and skill mastery in complex, high-risk industries.

A "Serious Game" (SG) of "Risk Hunting" on a tablet is proposed. However, it faces challenges with user acceptance, particularly among those less familiar with technology, and issues with content realism for more tech-savvy users. Despite digital tools validating theoretical knowledge, practical training in immersive VR environments remains crucial for addressing real-world conditions and has gained interest in the construction industry due to advancements in immersive Head Mounted Display (HMD) technology (Sacks et al. 2013; Wang et al. 2018). This is particularly important as creating more immersive and engaging environments has been shown to significantly enhance the learning experience and better simulate the complexities of real-world scenarios. Studies indicate that higher levels of immersion can improve user engagement, knowledge retention, and skill acquisition, making VR-based training more effective for professional development in construction and other fields (Whyte and Nikolic 2018; Zaharim and Mohamed 2020).

1.4 Virtual environment for training

One of the innovations implemented in recent years is training in an immersive virtual environment (VE). This technology has attracted the interest of several sectors due to the existence of Head Mounted Display (HMD) immersive headsets. The term “Virtual Reality” (*VR*) was introduced in 1989 by Jaron Lanier (Schroeder 1993). It is described by Fuchs and Moreau (Fuchs et al. 2006) as a scientific and technical field that exploits several skills such as computer science or electronics, providing a broad understanding of VR’s technical foundation but lacking specific applications. It is also presented by Bourdakis as an artificial environment generated by computer and presented to the user who perceives it as real (Bourdakis 1997), which clarifies the conceptual basis of VR but does not address its practical implementation.

VR is widely used in industry. There are several examples in the automotive and aerospace industries for design and maintenance assistance (Zimmermann 2008; Savall et al. 2002). Zimmermann and Savall highlight VR’s application for design and maintenance in these sectors, demonstrating its practical use but not addressing broader applications or effectiveness in other areas. Other use cases also exist for training, including surgeon training or military training (Kozlak et al. 2013; Bhagat et al. 2016), and security agents’ training (Passos et al. 2017). Kozlak and Bhagat show VR’s effectiveness in specialized training environments, though their studies are limited to specific fields without exploring general training applications.

In the construction industry, one of the first uses of VR was for design assistance, offering a full-scale visual of projects that were previously projected on conventional screens (Martin 2016). Martin illustrates how VR aids in design validation, but this application is focused on design rather than training. It thus allows validation of technical choices (Petrova et al. 2017) (location of technical ducts, coordination of different trades, ...) and architectural validation (choice of murals, furniture, ...). Petrova’s study emphasizes VR’s role in project planning but does not address its use for practical training.

Recently, VR has been used as a support for risk prevention and hazardous situations in controlled environments (HaiyanXie et al. 2006; Hilfert et al. 2016). Haiyan Xie and Hilfert demonstrate VR’s effectiveness in hazard awareness and risk prevention in construction, though their studies are limited to specific scenarios. However, training in construction is not limited to this; it is also important to be trained in the different processes of using tools and understanding tasks (Zhao et al. 2009). Zhao presents a simulation of electric shock risk, discussing VR’s potential for enhancing

safety awareness but focusing narrowly on electric shock risks.

Several simulators have emerged, based on the model of video games (Wang et al. 2011). Some displayed on screen and others in VR headsets, these simulators are based on real command interfaces and motion platforms for more immersion and realism in order to best transcribe real sensations (Patrão and Menezes 2013; Zhonghua et al. 2008). This parallel with the world of video games allows the creation of scenarios from the most common to the least usual operations, and at a lower cost. Wang et al. (2011) and Patrão and Menezes (2013) discuss the benefits of VR simulators for realistic training scenarios, though they do not address the limitations of VR in replicating specific real-world conditions.

The industry has also taken an interest in VR and its contribution to training and awareness of occupational hazards such as electrical hazards or working at height. For example, Hilfert et al. (2016) offers a tool for evaluating the behavior of workers near construction equipment by immersing them in a virtual environment created from a *Building Information Modeling* (BIM) model. BIM is a groundbreaking approach that involves the digital creation and management of a building’s information throughout its lifecycle. By integrating geometric, temporal, and financial data, BIM facilitates collaboration among various project stakeholders, leading to better planning, execution, and maintenance of constructions (Eastman et al. 2011). This methodology has rapidly become a standard in the construction industry, offering powerful tools for visualization and analysis, which in turn reduce errors and associated costs (Kymmell 2008). Hilfert’s tool allows for analysis, evaluation, and awareness of the risks of proximity to machinery (Hilfert et al. 2016), highlighting VR’s potential in risk assessment but focusing on a specific application.

Zhao presents a simulation of electric shock risk and discusses VR’s effects in cognitive conditioning, making this type of experimentation a valuable tool for safety awareness (Zhao et al. 2009). Zhao’s study illustrates VR’s role in cognitive conditioning for safety but is limited to specific hazards. In his article, Subedi describes a method of ergonomic analysis combining VR and posture monitoring. The author uses measurements and video captures of workers in various lifting postures and injects this data into a virtual environment to provide personalized feedback, raising awareness of health risks related to specific tasks (Subedi et al. 2017). Subedi’s approach highlights the use of VR for ergonomic training but is limited to specific postural analysis.

VR is a good learning tool that can complement traditional training methods: the theoretical part, in the classroom with video support, and the practical part, in the field by handling the actual tools. For instance, Tichon explored

plant operators' training in a virtual environment as an alternative to current training methods (Tichon and Diver 2010). Tichon's study investigates VR as an alternative training tool but does not compare it directly to traditional methods. However, some tasks, beyond understanding the process, require an understanding of the risks, particularly those related to actions and posture (Subedi et al. 2017). VR alone can be ineffective if not complemented by force feedback tools, addressing the need for additional sensory inputs to enhance training realism.

1.5 VR and haptic feedback

The notion of interaction, an important component in the sensation of presence, involves different sensory channels. The most widespread VR tools essentially rely on visual immersion, through stereoscopic display in 3 dimensions, and auditory immersion, through interactivity or spatialization of sound. Research, still in its early stages, also integrates olfactory and gustatory sensations (Burdea and Coiffet 2003). However, the sense of touch is more and more taken into account and integrated in immersive applications (Burdea and Coiffet 2003). Indeed, simulators including haptic feedback platforms are recognized and used to reproduce real situations requiring manual manipulation (Burdea 1999). Burdea describes haptic feedback as including force feedback, tactile feedback and proprioceptive feedback. Force feedback conveys information such as the weight or texture of a virtual object. Tactile feedback allows the user to perceive surface characteristics, geometry, smoothness, or temperature. Proprioceptive feedback provides information about the position and posture of the user's body. A history of the first applications in VR integrating a haptic feedback device is described by haptic feedback device is described by the author in his article (Burdea 1999). Burdea and Coiffet argue that adding haptic feedback to an immersive experience greatly amplifies the realism of the simulation (Burdea and Coiffet 2003). In their book, they focus on the sensations at the level of the hand, the part of the body with the highest density of tactile receptors. They explain in particular that according to the effort applied by the user, the neurological response is made either by the tactile receptors for light supports, or by kinesthetic response at the level of the muscles and bones for the more important supports. In human-computer interaction, visual and sound feedback is effective and allows users to accomplish a number of tasks. However, as the intensity of the tasks increases, this feedback becomes insufficient (Nijholt and Reidsma 2011). Nijholt emphasizes that for high-intensity tasks in virtual reality (VR) training, haptic feedback is crucial for enhancing realism and user performance. Force feedback interfaces must be designed in such a way that they do not

cause accidents during use. Therefore, they must be rigidly fixed to prevent unexpected movement. The most common example, as described by Burdea, is that of force feedback gloves, which are attached to the user's forearm to provide the necessary tactile feedback (Burdea and Coiffet 2003).

Several use cases including haptic simulators have emerged. There are for example, automotive simulators. Jensen presents a driving simulator based on screens and a simple model of a vehicle, with the seat, the steering wheel and the pedals (Jensen et al. 2011). This simulator is used to measure the response times of a user having to avoid an obstacle. Haptic simulators are widely used in medicine, for training surgeons or dentists. Wang describes in his article (Wang et al. 2006) a simulation of a neurosurgery operation combining VR and haptic feedback. The author concludes that the use of such a system could achieve a degree of realism important enough to be used for the training of neurosurgeons. For dentistry, Roy states that force feedback systems associated with VR could complement traditional training methods for dentists (Roy et al. 2017). Pohlenz conducted studies with 53 dental students. He offered a dental implant preparation simulator. The results of his study showed that more than 92% of the participants recommended the use of this type of tool for training and more than 81% of them considered the simulator to be good or very good and fairly realistic (Pohlenz et al. 2010). The combination of a force feedback platform with VR is widely used in patient in the rehabilitation of patients. For instance, the work of Frisoli presents a neuro-rehabilitation system based on an exoskeleton and a VR whose scenarios are imagined by specialized therapists. He evaluated his system with eight patients suffering from a cerebral vascular accident. The results are promising and the author concludes that this system provides a significant benefit in the recovery of upper limb function (Frisoli et al. 2009).

1.6 Needs and state of the art

A human interacts with a system through different channels (e.g., vocal, manual, or other interactive means). In turn, the system provides feedback to the user, which can take various forms such as visual or auditory signals.

As described before, VR is an interesting tool for training. It allows, in controlled situation, to train the construction worker, and to allow him to go up in competence. It can be used to train in realistic situations by offering a visual and auditory immersion. It can concern exercises of dangerous situation, as well as training on operating mode of tools use. It allows to satisfy the 3 parties by providing adequate feedback.

In VR-based training, the trainee interacts with the virtual environment using a head-mounted display (HMD),

with interactions performed via associated input devices such as handheld controllers or hand-tracking systems. The system conveys the effects of the trainee's actions back to them through the HMD, primarily as visual feedback and, in some cases, auditory cues.

Yet, when evaluating posture, VR alone is not sufficient. For instance, lifting a virtual panel without resistance does not accurately reflect real muscular effort or risk. To observe meaningful reactions, the trainee must perform real actions. The absence of actual physical stress, effort, or resistance in VR prevents the trainee from fully understanding the task and limits ergonomists' and trainers' ability to assess the construction worker's response to effort. Consequently, performance indicators and metrics obtained from VR alone may be unreliable.

The question then is how to provide a quantitative method, based on VR, of evaluating trainees during motion and posture training.

To address this issue (Fig. 3), a robotic platform was designed that would include, in addition to the visual immersion guaranteed by the VR HMD, a tactile sensation and force feedback.

The interaction of the user with the system, represented here by the robotic platform, has been done by means of tools which ensure, in addition to the visual feedback of the HMD, a force feedback.

The objective of this study is to evaluate the impact of using different modalities (VR alone and VR with force feedback robotic platform) in the learning and understanding by the user of the risks related to a task. Our hypothesis is that engaging the sense of touch and stimulating muscles through force feedback improves task understanding and raises awareness of risks related to posture and effort.

2 Contribution

In this study, conducted in collaboration with construction workers, the objective is to develop a training approach focused on correct gestures and postures during formwork panel handling. Current training relies on a combination of theoretical and practical sessions. During the theoretical phase, trainers introduce the panel, its installation

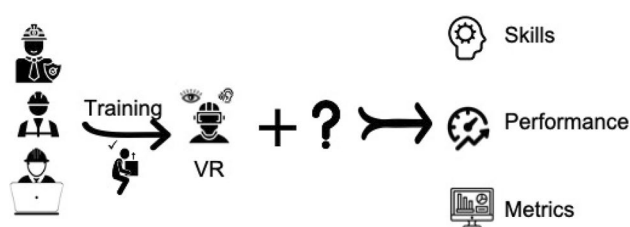


Fig. 3 Principle of the posture training methodology

procedures, and the associated risks. The practical phase then allows workers to apply this knowledge using real equipment, either on site or in training centers. However, exposing trainees to hazardous situations in real conditions remains difficult, limiting the effectiveness of risk awareness during practical training.

Virtual reality (VR) therefore appears as a relevant alternative for reproducing risky scenarios in a controlled and safe environment. Nevertheless, for health risk awareness, VR used without sufficient contextual information or tactile feedback has shown limited effectiveness for populations accustomed to physically demanding tasks. Kjeldskov and Graham (Kjeldskov and Graham 2019) demonstrated that the absence of tactile feedback in VR environments significantly reduces engagement and retention in high-risk occupations such as construction. This observation is consistent with feedback from industry experts, who emphasize that realistic sensory cues are essential for meaningful risk perception. Similarly, Hollis, O'Neill, and Turner showed that VR simulations lacking tactile and contextual feedback often fail to engage users familiar with real-world physical constraints (Hollis et al. 2020).

Integrating haptic feedback into VR training therefore constitutes a promising approach for improving ergonomic awareness and safety. When posture evaluation is concerned, VR alone remains insufficient: without physical effort, resistance, or counter-action, trainees cannot fully apprehend task demands, and trainers and ergonomists cannot reliably assess reactions to effort. As a result, performance indicators derived solely from visual VR interactions may be unreliable. This limitation is particularly critical in construction activities, where musculoskeletal disorders (MSDs) frequently result from repetitive movements, awkward postures, and heavy loads.

Haptic-enhanced VR training enables workers to experience realistic physical constraints while remaining in a safe environment. Such systems allow users to practice correct tool handling and posture under simulated load conditions, thereby reinforcing ergonomic principles without exposure to real hazards. One key advantage lies in the ability to provide real-time feedback on biomechanical movements: haptic devices can signal improper postures or excessive force, facilitating immediate correction and supporting safer habit formation (Sharma and Haskins 2015).

Beyond immediate feedback, haptic simulation fosters a deeper understanding of the body's physical limits by reproducing the weight and resistance of tools and materials. This kinesthetic experience enhances spatial awareness and hand-eye coordination, which are critical for precision tasks in construction (Zhou and Wang 2016). Moreover, by introducing varying levels of effort and constraint, haptic VR environments help trainees manage cognitive load and

improve decision-making under pressure, a key requirement in complex and dynamic work situations (Miller and Smith 2007).

In addition to physical benefits, haptic VR training can positively influence safety culture and psychological factors. Training in a realistic yet controlled environment increases confidence, reduces anxiety related to injury risk, and encourages proactive safety behaviors on site (Hakkinen and Laaksonen 2011).

Based on these considerations, Virtual Compagnon is proposed. This system combines a realistic virtual environment for visual immersion with a robotic platform providing force feedback, complemented by a motion analysis system to support trainers and ergonomists during training and awareness activities. The motion analysis component is not addressed in the present article (Fig. 3).

2.1 The formwork panel

Formwork panels are tools appeared in the xviith century (López-Arquillos et al. 2014). They are posed face to face and are used to mould with concrete, generally reinforced, parts of thick wall sections. There are several possible configurations with widths of 2.4 m, 1,2 m and 0.6 m with heights of 2.85 m, 1,5 m, 1 m or 0.5 m. The formwork panel used in this work is a panel of 1.2 m in width and 2.85 m in height.

The choice of this particular equipment was suggested by the industrial partner's trainers and ergonomists. This choice is encouraged by the complexity of this tool due to the fact that there are many procedures for setting up the formwork. These range from the placement of ballast, concrete pouring, reinforcement placement and rod tightening

All the steps of the formwork panel installation procedure represent a health and safety risk for the worker. One of the steps in the operation is the closing, or adjustment, of the panel with the crowbar (Fig. 4).

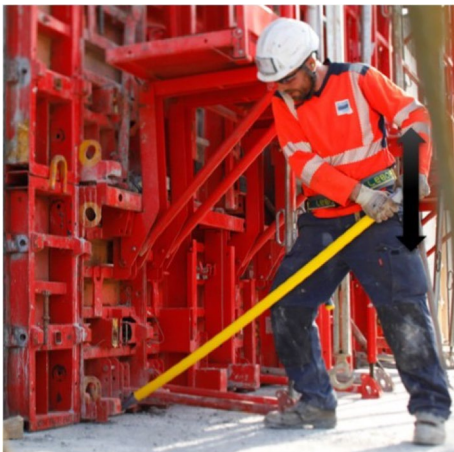


Fig. 4 A employee using the crowbar

The crowbar (Leborgne 2020) measures 1.75 m in height and 0,1 m in width and weighs 5.2 kg. It is made of an aluminum alloy handle and the heel and flame are made of forged steel. It has two different sides. The angle between these two sides is $\frac{3\pi}{4}$.

The use of the crowbar presents safety risks, such as the risk of falling on the same level or the risk of pinching, and health risks due to repetitive movements that can cause MSD. To meet this challenge, the company has taken a number of steps to limit these risks. This involves constant innovation on the work sites, awareness campaigns and training, among other things.

Yet, the use of the panel is still widespread. Since the crane cannot be at the service of the construction worker at all times, the workers must find a solution to move the panels. At the moment, there is no technological solution that allows to close the panels and that is mobile and easily transportable on a construction site. The crowbar remains the best solution to accomplish the task.

2.1.1 Current training program

The *Professional Title of Formworker*³, offered by the Gustave Eiffel Apprentice Training Center, is a comprehensive and structured program designed to cultivate essential skills for professionals in formwork within the construction industry. This certification focuses on equipping participants with practical expertise in creating concrete structures using various formwork systems, while also enhancing their understanding of the principles necessary to ensure the stability of constructions and compliance with safety regulations.

The training is designed with an innovative approach that combines theoretical and practical components, enabling participants to gain a well-rounded education. The curriculum includes in-depth lessons on the principles of formwork design, construction techniques, and material selection, as well as safety protocols essential for working on construction sites. Participants will also engage in hands-on training, where they can apply their knowledge in real-world settings, reinforcing their skills through practical exercises.

A distinctive feature of this program is its alternating rhythm, which integrates periods of classroom instruction with practical, on-site experiences. This format not only facilitates immediate application of learned concepts but also promotes deeper retention of knowledge. By alternating between theory and practice, participants can better understand the nuances of formwork construction, from the initial design phase to the final execution on site. This

³ The Gustave Eiffel Apprentice Center's Professional Title of Formworker Program: www.centregustaveeiffel.fr/titrepro-coffreur-bancheur

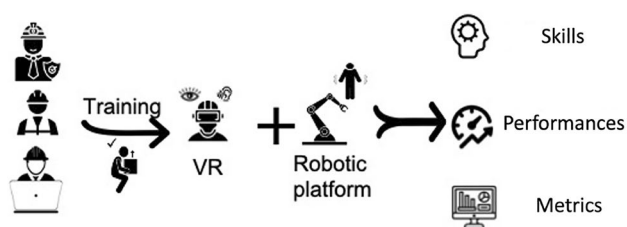


Fig. 5 Principle of the posture training methodology based on VR and haptic feedback

experiential learning approach prepares them to respond effectively to the challenges they will encounter in their professional careers.

Furthermore, the training addresses the evolving demands of the construction industry, especially in light of advancements in construction techniques and the increasing intensity of construction activities. As construction practices continue to evolve, the need for skilled professionals who can adapt to new technologies and methods has never been more critical. The program equips participants with the skills and knowledge required to meet these challenges head-on, ensuring that they are not only competent but also innovative in their approach to formwork.

Typically, a professional can be considered an expert formworker after acquiring a few years of dedicated practice in the field—often around one to two years. This period allows them to develop a solid understanding of formwork systems, safety standards, and industry best practices, positioning them as trusted specialists within the construction sector.

2.1.2 Virtual reality training for formwork panel handling

The use of virtual reality alone for formwork panel training may prove ineffective, as it will not accurately represent the effort needed to secure the sail with a crowbar. For the trainer and the ergonomist, it will not allow to evaluate quantitatively and efficiently the efforts made by the trainee and to evaluate his posture. In this case, by proposing as interaction modalities a VR environment, haptic feedback and a motion analysis system it can be ensured that

- Proposition 1: The construction worker is immersed in an environment he knows (construction site) and performs the tasks inspired by the real operating mode,
- Proposition 2: The robotic platform could reproduce an effort close to the real effort and by integrating the same tool as the one used on site: the crowbar. The construction worker is thus able to perform the real gesture in a secure environment,

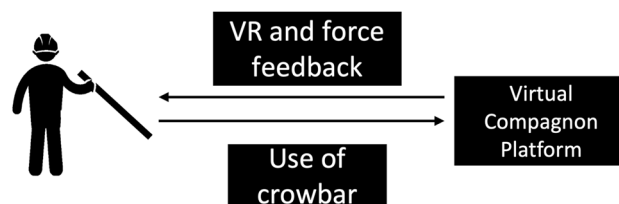


Fig. 6 Principle diagram of employee and *Virtual Compagnon* interaction

- Proposition 3: The trainer has the metrics that the platform sends back and the real time analysis of the movement to adapt his recommendations.

A system has been designed to be adaptable to the profile of the targeted user: the employee (Fig. 5).

The use of interaction devices that would be difficult for him to adapt to, was avoided. Therefore, the choice to respect the operating mode linked to the targeted task was made, including in the design the consideration of the employee's tool: the crowbar. The environment he is used to was recreated in VR : a construction site.

The principle of interaction of this case study is shown in Fig. 6.

The employee is thus facing a robotic platform that plays the role of the formwork panel and is supposed to reproduce its behavior. He is immersed in a virtual environment where the panel is represented. To interact with the environment and the platform, he uses the crowbar. This ensures that the employee is visually immersed and that he feels the efforts, as when he uses the crowbar with the formwork panel on site.

2.2 System features

2.2.1 The virtual environment

The virtual environment (VE) is an important component of the proposed application. Indeed, the VE allows two things:

1. The visual and auditory immersion of the construction worker into an environment he knows,
2. The visualization of the actions he performs with the crowbar for more realism.

For the first point, a construction site environment from a 3D model extracted from the BIM model was reproduced (Fig. 7). The construction worker knows the construction site well. Therefore, the VE should be as close as possible. Burkhardt (Burkhardt 2003) asserts that a realistic VR simulation is efficient and convincing if the target has mastered the task and is familiar with its context.

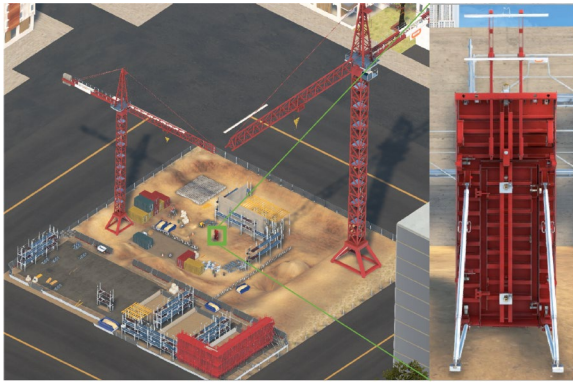


Fig. 7 The virtual environment and the 3D reproduction of the formwork panel (on the right)



Fig. 8 The robotic platform of *Virtual Companion* with its two robotized sides

This representation makes it possible to immerse the construction worker in his working environment. It must be fairly realistic.

He will find the tools and machines that he knows and with which he will have to work in reality. A sound environment is also added to reinforce the visual immersion by a sound immersion.

2.2.2 The robotic platform

VR provides visual and auditory immersion to the user. He can be projected in an environment recreated by a computer and interact with the elements that compose it. In the application, the construction worker is projected in a construction site environment. He is surrounded by the tools and elements he uses every day. He hears the sounds of the machines he is working with. However, this immersion is not enough to make him aware of the importance of a posture when using the crowbar to close the panel. To realize the effort involved in accomplishing this task, a system that allows him to feel this effort must be integrated. This system also allows the trainers to evaluate the performance of the trainees during the training. Finally, for the ergonomist, the system is able to integrate a motion tracking device in order to evaluate the trainee's posture in a more realistic way, and based on quantitative data.

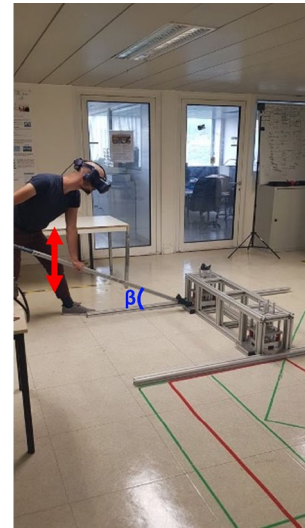


Fig. 9 Use of the robotic platform with the crowbar—Case study to test the hypothesis

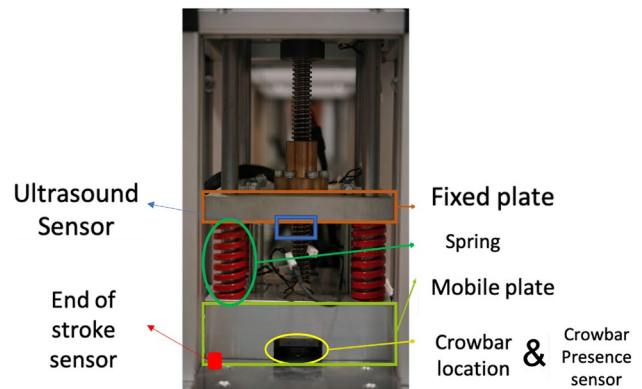


Fig. 10 The robotic platform of *Virtual Companion*

This system is a robotic platform that replaces the formwork panel. It is more mobile and secure than the real tool.

The platform (Fig. 8) is a combination of mechanical and electronic components that ensure, on the one hand, the reproduction of the effort during the use of the crowbar (Fig. 9).

On the other hand, the communication with the VE in order to transmit the movements to the 3D model of the panel to ensure consistency between the action and what is perceived by the user in the HMD.

To ensure that the construction worker perceives the correct level of effort during training, high-stiffness springs (156kN m) were used between two plates - one fixed and one mobile. When (Fig. 10) the worker operates the crowbar, these springs are compressed, providing a realistic simulation of physical effort. This setup helps in creating an authentic training experience by mimicking the physical effort required on-site.

For seamless interaction with the virtual environment (VE), the platform integrates advanced sensor technology. These sensors, connected through microcontrollers boards, play a crucial role:

- Bar Presence Sensor: Detects which side the worker is operating on.
- End-of-Stroke Sensor: Monitors the position of the panel relative to the ground.
- Distance Sensor: Measures the lift distance and, consequently, the compression of the springs.

The platform is also equipped with two Brushless DC motors, each operating at 24V and providing 30W of power. These motors are equipped with a 3-stage planetary gearbox, which allows them to deliver a maximum torque of 30N m, essential for handling various load conditions. The motor output speed is 7 RPM, and they draw a nominal current of 6A. While the platform can function effectively in a passive mode, these motors are crucial for assisting in the return of the mobile plate to its starting position, as the spring decompression is slow and requires mechanical support to simulate gravity.

2.2.3 Passive mode

In passive mode, the motors play a vital role in facilitating the return of the mobile plate to its initial position. The decompression of the high-stiffness springs is inherently slow, which delays the plate's movement. To address this, mechanical assistance is provided by the motors to compensate for the lack of gravitational pull, which is typically absent in controlled training environments. This mechanical support is essential to simulate the effects of gravity accurately, ensuring that the system behaves as it would in a real-world scenario. Without the motors' intervention, the return process would be inefficient, reducing the overall realism and effectiveness of the training simulation (Fig. 10).

2.2.4 Assistance mode

In the assistance mode, the goal is to reduce the effort required by the user, making it easier to handle the platform, which is beneficial for beginners or scenarios requiring less physical effort. This mode can be simulated by:

- Programming the Brushless DC motors to operate at lower speeds and reduced torque. For example, if the normal operating speed is 7 RPM, in Assistance Mode, this speed might be reduced to 3 RPM. The torque setting might be decreased to 15 N m, compared to the

maximum 30 N m. This reduction helps simulate lighter load conditions or external assistance such as a crane.

- Reconfiguring the motor driver settings to provide smooth and gradual assistance. For instance, reducing the current supplied to the motors from 6 to 3 A lowers their power output. The control system algorithms adjust the motor's response to facilitate user movements, making it easier to manipulate the platform with less physical effort.
- Simulating external aids such as cranes by adjusting the load profile. For example, the system can be calibrated to emulate the effect of a crane lifting part of the load, reducing the perceived effort required by the user.

2.2.5 Resistive mode

In the resistive mode, the focus is on increasing the resistance to simulate heavier loads, thereby providing a more challenging training experience. This mode can be simulated by:

- Reconfiguring the motors to operate at higher torque and speed levels. For example, instead of the standard 7 RPM, the motors could be adjusted to 10 RPM, and the torque could be increased to 35 N m. This adjustment ensures that the platform provides greater resistance, simulating the effect of heavier loads.
- Programming the system to simulate high-effort tasks. For instance, if moving a heavy panel without crane support is required, the motors can be set to provide consistent resistance that mimics the full weight of the panel, forcing the user to exert more effort.
- Adjusting resistance profiles to simulate different scenarios. For example, a profile might be created to simulate lifting a panel in a confined space with high friction, requiring the motors to apply varying degrees of resistance based on the specific training scenario.

By adjusting the motor parameters and control strategies for each mode, the platform offers a versatile training experience. Assistance Mode helps users become familiar with the system and facilitates learning, while Resistive Mode prepares them for more demanding tasks by simulating realistic, high-effort scenarios. This flexibility ensures that the training platform effectively addresses a range of skill levels and training objectives.

2.2.6 Motion tracking

A motion capture function is integrated in *Virtual Companion*. Motion Capture (MoCap) is a technique that allows to follow the position or orientation of an object or a person.

This capture is rendered in real time via the rendering engine specific to the equipment and can be recorded in a format that can be used by 3D software. The different hardware available on the market allows to capture body movements, facial expressions, finger movements

Motion capture techniques can be classified into four categories: optical, mechanical, magnetic and gyroscopic. In this case, two different technologies were compared: VICON and the TEA Captiv solution.

VICON is an optical motion capture system. To use it, markers are placed on the object or person to be tracked at certain points (Fig. 11a). For tracking body movements, these markers are placed near the joints. To capture these points, infrared cameras are used (Fig. 11b). The cameras send infrared rays that are reflected by the markers to the same cameras. The coordinates of the points are deduced by triangulation. A minimum of two cameras is required for the software to deduce them. Thus, when a point is visible, it appears on the processing software as of an illuminated pixel relative to the background. Each point has a unique identifier, which can be used in post-processing to recognize the different parts of the body. It is thus possible to reconstruct the skeleton by forming an axis connecting the points.

The system is installed in the laboratory and is fixed and cannot be moved.

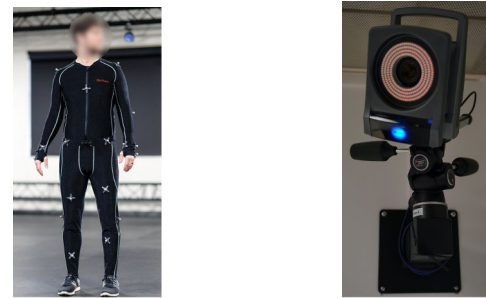
The TEA Captiv is a mobile software and hardware solution developed by “Tech Ergo Appliquées” (TEA) and used by the industrial partner’s. The solution is used for the analysis of workstations in real activity situations thanks to wireless sensors placed directly on the directly on the body of the observed subject (Fig. 12a). An external box allows the synchronization and data recording (Fig. 12b).

The whole is accompanied by a software solution that also allows to apply the collected data to an avatar for a more visual analysis. A number of tools, based on health data, are also available for quantitative motion analysis.

3 Method

3.1 Evaluation procedure

In order to evaluate the contribution of different configuration proposed for the training, a questionnaire were drafted. The objective of this questionnaire is, on the one hand, to collect the participants’ opinion on the haptic and VR approach. On the other hand, the objective is to evaluate the contribution of the different tools used. For this, the questionnaire was scored and administered to two groups (novices and professionals). The groups have a different level of knowledge of the formwork panel and the construction industry. They also have different sensitivities to the



(a) Markers placed

(b) Infrared camera

Fig. 11 VICON system [Source : www.vicon.com]



(a) Motion sensor

(b) Data acquisition system

Fig. 12 TEA solution [Source : www.teaergo.com]

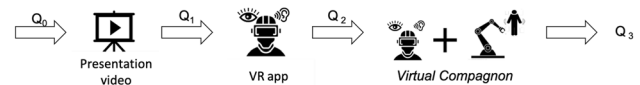


Fig. 13 Procedure followed for the experiment—the industrial partner’s protocol

technologies presented. The questionnaire is submitted 4 times using three different information support. (Fig. 13).

- The questionnaire (Q_0) is presented to the participant at the beginning of the experiment. Its purpose is to assess his or her basic knowledge.
- Then, a video of a few minutes is shown. It presents the properties of the formwork panel and the different steps of the installation, in particular, the use of the crowbar. At the end of this video, the questionnaire is presented again (Q_1). This one allows to evaluate the knowledge provided by the video.
- The participant is then equipped with the VR headset, and a VR application on the formwork panel, and more particularly the closing of the veil with the crowbar, is launched. He has to grab a virtual crowbar, and repeat the gesture he saw in the video presented before. Once the exercise is completed, he answers the questionnaire (Q_2). The purpose of this questionnaire is to compare the knowledge acquired by the video and compare the results to the first two questionnaires.
- Finally, during the last step, the participant is equipped with sensors, gloves and a VR helmet. The VR application is launched. He grabs the real crowbar, and performs the task, repeating the gesture he saw in the video, with this time, a force feedback provided by the robotic platform. The last questionnaire (Q_3) is submitted after

the end of the exercise. Its purpose will be to evaluate this last approach and to compare it to the other methods.

The various information supports are described in Table 1.

The questions cover two topics: general knowledge and knowledge of the hazards associated with the use of the panel and crowbar.

- General knowledge will cover the use and dimensions of the tools (formwork panel and crowbar).
- Hazard knowledge is related to knowledge of the hazards associated with the use of these tools.

For the novices, the interest is to know if the use of such a tool is relevant for the learning of the methodology, the risk and the good gesture. For the professionals, an evaluation of the formworkers' knowledge is aimed, to bring them a new means of sensitization and training in the gestures. It is also a tool for trainers to bring metrics to the current training.

3.2 Protocol

The protocol is part of the industrial partner's training procedure implemented by ergonomists.

A serie of questionnaires were administered to two groups: a group of novices (Group 1, fifteen people) and a group of professionals (Group 2, ten people).

The first group could not have been invited to the training center. Also, in order to use the VICON, the test had to be conducted in the laboratory. For this, Group 1 participated in the laboratory test (Fig. 14). The participants have no knowledge of the construction industry and have never worked on the formwork panel or used the crowbar. Their characteristics are reported in Table 2.

Group 2, all males, were trainees at the apprentice training center. The group chosen for the experiment has been recommended by the trainer and their experience has been validated by him (Fig. 15). The aim is to test the system with people who know the tool and how it works but also the acceptance of the method by a public not very receptive to digital tools.

The test was conducted at the training center during their training. They know the site and have, for the most part, practiced the formwork panel. Their characteristics are reported in Table 3.

3.3 Limitations

In this study, we concentrated exclusively on gathering and analyzing user feedback to evaluate the effectiveness of the training methodology. We did not incorporate other performance measures, such as objective assessments of

Table 1 Order of completion of the questionnaires and the tools used

Questionnaire	Description
Q ₀	The first questionnaire is proposed to the participants upon their arrival. This questionnaire is used to assess the basic knowledge of each person
Q ₁	The second questionnaire is proposed at the end of the video. The video shows the different steps of the assembly of the formwork panel
Q ₂	During this stage, the participant is immersed in a virtual environment thanks to the HTC Vive headset. He manipulates a virtual crowbar and moves the formwork panel. The exercise is stopped after two minutes and the participant answers the third questionnaire
Q ₃	During this stage, the participant is equipped with the HTC Vive helmet. He uses the real crowbar and acts on the robotic platform. He answers the last questionnaire at the end of the manipulation and is invited to note his comments



Fig. 14 A participant being tested on the platform in the laboratory

skill proficiency or longitudinal performance tracking. This focus on user feedback alone represents a limitation of our study. Future research should consider integrating a wider range of evaluation metrics to provide a more comprehensive assessment of trainee performance and the overall efficacy of the training approach.

3.4 Assessment results

Three different studies were conducted: a full questionnaire study, a study focusing only on the main questions, and a study focusing only on the secondary questions.

For each study, two parameters were studied. On the one hand, the average scores for each group. On the other hand, score gains.

Table 2 Characteristics of participants in the novice group (Group 1)

Participant	Gender	Age
1	M	25
2	F	26
3	M	34
4	M	42
5	M	26
6	M	26
7	M	25
8	M	27
9	F	20
10	F	46
11	M	47
12	F	17
13	M	25
14	M	27
15	F	42



Fig. 15 A construction worker being tested on the platform at the training center

Table 3 Characteristics of participants in the Professionals group (Group 2)

Participant	Age	On-site experience (months)
1	44	3
2	27	3
3	52	3
4	41	3
5	42	3
6	47	3
7	28	3
8	21	3
9	22	3
10	27	3

Score gains are the difference in score between sessions, (i.e. $Q_n - Q_{n-1}$). This is used to observe whether there is an improvement in the score from one session to another, depending on the tools offered.

In the following, the analysis of the complete questionnaire is presented.

Table 4 Mean and standard deviation of the novice group

Novice	Q_0	Q_1	Q_2	Q_3
Mean	10,8	22,4	24,5	28,6
Standard deviation	10	8,3	5	5,9

Table 5 Mean and standard deviation of the professional group

Professional	Q_0	Q_1	Q_2	Q_3
Mean	41,5	44,5	44,5	47,6
Standard deviation	21,3	21,9	20,1	21

Table 6 Type III test of fixed effects

Effects	DoF's numerator	DoF's denominator	F	Pr > F
Group	1	92	16,306	0,0001
Time	3	92	38,468	<0,0001
Group × Time	3	92	8,379	<0,0001

3.5 Average scores

The average score of all participants for each session was calculated.

For the novice group, the means and standard deviations of the scores are reported in Table 4.

For professionals (Group 2), the means and standard deviations of the scores are reported in Table 5.

To compare groups, a repeated measures ANOVA is applied using mixed models. The dependent variable is the score. The explanatory variables are time (Q_n) and group factor (Novices and Professionals). The significance of the interaction “group × time” was measured (Table 6).

The value found ($p < 0.05$) shows that the effect is significant. This means that the effect of the session is not the same depending on the group. Therefore, the study on each group separately to evaluate the effect of time (which corresponds to the session Q_n) has to be conducted. There is a significant effect of the interaction *Group × Time* which means that the effect of the session is not the same according to the groups (Fig. 16).

The effect of time on each group is therefore analyzed separately. To do so, the model is checked.

Figure 17 shows three extreme points of the group. However, the plot follows the diagonal. The residuals can be considered to be approximately Gaussian and therefore the model assumptions are verified. A normality test by Shapiro–Wilk rejects the hypothesis that the sample follows a normal distribution ($p < 0.0001$) because of these points.

Three points on the right side of the diagram stand out from the rest. These points correspond to a subject with very good results. It influences the analysis because a Shapiro–Wilk test without it is no longer significant ($p = 0.072$).

To analyze the effect of time on each group separately, ANOVA using mixed models is used, for each group, a repeated measures and if the conditions are not verified,

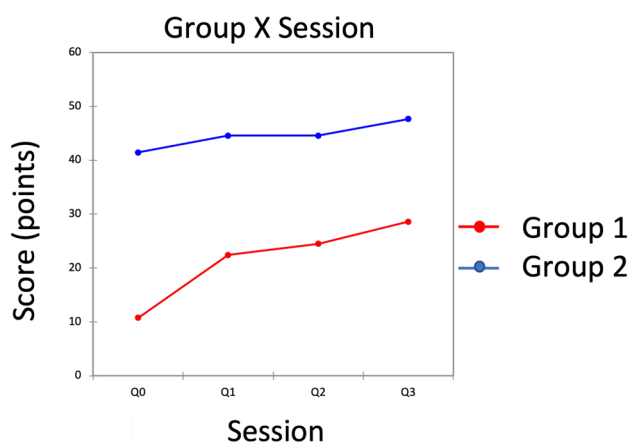
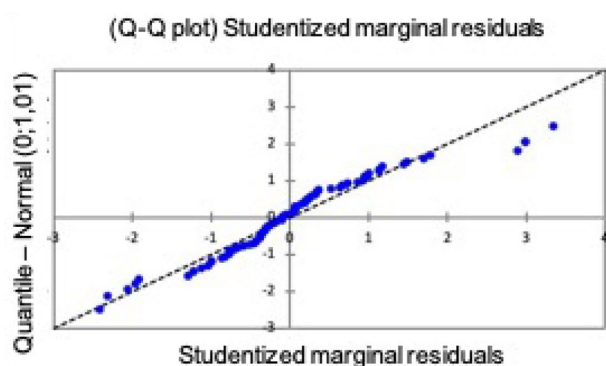
Fig. 16 Group \times Session interaction

Fig. 17 Plot of Student's normalized residuals—3 extreme points on the right side of the Fig.

Table 7 Friedman's test for the novice group

Q (Observed value)	36,021
Q (Critical value)	7,815
<i>p</i> -value (bilateral)	<0,0001
Alpha	0,05

Table 8 *p*-values of Nemenyi's post-hoc tests

	Q ₀	Q ₁	Q ₂	Q ₃
Q ₀	1	0,001	0,0003	0,0001
Q ₁	0,001	1	0,777	0,013
Q ₂	0,0003	0,777	1	0,028
Q ₃	0,0001	0,013	0,028	1

Bonferroni-corrected significance level: 0.0083

a Friedman test is applied. The dependent variable is the score. The explanatory variable is the time factor.

For novices (Group 1), the results of the Friedman's test are reported in Table 7.

The difference between the session averages is significant ($p < 0.0001$).

To check which means are different, Nemenyi's post-hoc tests is applied (Table 8).

Table 9 Type III test of fixed effects

Effects	DoF's numerator	DoF's denominator	F	Pr > F
Time	3	36	4,516	0,009

Table 10 Time/Tukey (HSD)/Analysis of differences between modalities with 95% confidence interval

Contrast	Difference	Standard error	t	Pr > t	Significant
Q ₃ vs Q ₀	6,182	1,680	2,693	0,004	Yes
Q ₃ vs Q ₂	3,091	1,680	2,693	0,272	No
Q ₂ vs Q ₁	3,091	1,680	2,693	0,272	No
Q ₂ vs Q ₀	3,091	1,680	2,693	0,272	No
Q ₂ vs Q ₁	0,000	1,680	2,693	1,000	No
Q ₁ vs Q ₀	3,091	1,680	2,693	0,272	Non

Critical value of Tukey's *d*: 3,809Table 11 *p*-values found by Friedman's test

	Q ₀	Q ₁	Q ₂	Q ₃
Q ₀	1	0,083	0,299	0,006
Q ₁	0,083	1	0,488	0,299
Q ₂	0,299	0,488	1	0,083
Q ₃	0,006	0,299	0,083	1

Bonferroni-corrected significance level: 0.0083

Table 12 Mean and standard deviation of score gains Q_n-Q_{n-1} for the novice group

Novices	Q ₁ -Q ₀	Q ₂ -Q ₁	Q ₃ -Q ₂
Mean	12,5	1,8	4,8
Standard deviation	6,9	5,3	3,7

For professionals, the mixed model is checked.

A test of type III of fixed effects is applied (Table 9).

To observe which averages are different, Tuckey's post-hoc tests (HSD) is applied (Table 10).

The only significant difference is between Q₀ and Q₃. This result is confirmed by a Friedman's test (Table 11).

3.6 Score gains

In order to comply with the training procedure, the order in which the materials were handed out was not randomized. Therefore, a cumulative effect is studied. Thus, with Q₁ the effect of tool 1 could be measured with respect to Q₀, with Q₂ the effect could be measured with respect to Q₁ of tool 2

For each subject, the effect of a given tool will be determined by the difference in score between the session preceding the tool and the session following the tool used. Thus, the effect of tool 2 will be obtained by calculating the difference between the score at Q₁ and the score at Q₂. This is the score gain between each session. The means and standard deviations of the gains of Q_n-Q_{n-1} are reported in Table 12.

The means and standard deviations of the Q_n-Q_{n-1} score gains are reported Table 13.

In order to analyze the gains between sessions, a repeated measures ANOVA using mixed models is applied. The dependent variable is the gain between two successive sessions. The dependent variable is the score. The explanatory variables are time (Q_n) and group factor (Novices and Professionals). The significance of the interaction "group \times time" is measured (Table 14).

There is no interaction effect $Group \times Time$. Yet, two things has been noticed: there is a group effect ($p < 0.05$). This means that earnings differ between groups.

There is also a time effect ($p < 0.05$). The gains differ between sessions.

To observe the two-by-two differences in earnings between groups, Tuckey's post-hoc tests (HSD) is applied (Table 15).

An analysis of differences shows that the earnings of the "novice" group are higher on average than those of the "professional" group. This is explained by the fact that the novice groups have no knowledge of the job site at the beginning of the test and therefore learn more each time a new tool is added.

To observe two-by-two differences in earnings across groups, Tuckey's post-hoc tests (HSD) is applied (Table 16).

According to Table 14, the interaction "group \times time" is not significant but close to 0.05 ($p = 0.067$). To complete the study, the groups are separated.

To analyze the effect of time on each group separately, a Friedman test for each group is applied.

For the novice groups, the results are reported in Table 17.

Nemenyi's post-hoc tests are applied to observe which average gains are different (Tab 18).

The Friedman test for professionals is applied (Table 19)

Participants' written comments are collected by asking them to answer the last question on the questionnaire at the end of the experiment.

4 Discussion

According to Table 16, the gains Q_1-Q_0 differ significantly from Q_2-Q_1 and Q_3-Q_2 . This can be explained by the fact that the gain in session 1 compared to session 0 is greater than the gains between the other sessions, due to learning and the capping of scores. A form of learning convergence. For novices, the difference in average session gains differs significantly ($p < 0.05$) (Table 18). It is again Q_1-Q_0 that differs significantly from Q_2-Q_1 and from Q_3-Q_2 . Indeed, having no knowledge of the construction sector, novices acquire a certain knowledge as soon as they pass the first tool. In the following, they simply capitalize

Table 13 Average and standard deviation of score gains Q_n-Q_{n-1} of the professional group

Professionals	Q_1-Q_0	Q_2-Q_1	Q_3-Q_2
Mean	3,1	0	3,1
Standard deviation	6,4	5,6	4,4

Table 14 Type III test of fixed effects

Effects	DoF's numerator	DoF's denominator	F	Pr > F
Group	1	69	11,756	0,001
Time	2	69	8,857	0,0004
Group \times Time	2	69	2,816	0,067

Table 15 Time/Tukey (HSD)/Analysis of differences between modalities with 95% confidence interval

Contrast	Difference	Standard error	t	Pr > t	Significant
Novices vs Professionals	3,879	1,189	1,995	0,002	Yes

Critical value of Tukey's d: 2,821

Table 16 Time/Tukey (HSD)/Analysis of differences between modalities with 95% confidence interval

Contrast	Difference	Standard error	t	Pr > t	Significant
Q_1-Q_0 vs Q_2-Q_1	6,333	1,457	2,396	0,000	Yes
Q_1-Q_0 vs Q_3-Q_2	3,758	1,457	2,396	0,032	Yes
Q_2-Q_1 vs Q_3-Q_2	2,576	1,457	2,396	0,188	No

Critical value of Tukey's d : 3,388

Table 17 Friedman's test for the novice group

Q (Observed value)	17,517
Q (Critical value)	5,991
p-value (bilateral)	<0,0001
Alpha	0,05

Table 18 p-values calculated by Nemenyi's post-hoc tests

	Q_1-Q_0	Q_2-Q_1	Q_3-Q_2
Q_1-Q_0	1	0,0003	0,001
Q_2-Q_1	0,0003	1	0,855
Q_3-Q_2	0,001	0,855	0

Bonferroni's corrected significance level : 0,0167

Table 19 Friedman's test for the professional group

Q (Observed value)	2,737
Q (Critical value)	5,991
p-value (bilateral)	0,272
Alpha	0,05

on this knowledge and add elements of answers according to the tools presented afterwards. In addition to answering questions, participants were asked to comment on the experiment. This gave them the opportunity to express their feelings and suggest improvements.

A synthesis of the different comments from novices has been reported in Table 20.

The various comments from professionals has been reported in Table 21.

According to their comments, the novice participants all agree that the experiment gave them a better understanding of the work site context (Table 20). They appreciated the virtual environment and found it immersive. The progression in the experience was appreciated. It allowed them to understand the context, to practice in virtual and to practice with the real tool afterwards. This last phase was also well received. Participants were able to understand the risks associated with the use of the formwork panel and the crowbar. They felt the effort required to deploy it and the muscles that are used to do so.

Although the experience was well appreciated, a few points for improvement were suggested by the participants. Indeed, the proposed video is not suitable for a novice audience because it lacks information. Novices unfamiliar with the terrain also had difficulty projecting themselves and realizing the dimensions of the formwork panels. They would have liked to have elements of comparison to be able to answer certain questions.

The immersive experience was well received by professionals. They especially appreciated the immersion that the helmet offers. Most of them have never tried a VR helmet before. For them, it was a discovery of the technology. They struggled with the VR experience only. They were not accustomed to using the controllers and it took a little time to adapt, despite the explanatory text they read. For those who had little experience with the formwork panel in the field, the video allowed them to understand the procedure involved in implementing the formwork. That said, some say that the video was not complete and would have helped them very little in understanding certain aspects of answering the questions. The experiment combining VR and the robotic platform was well appreciated by the second group. They could see that it was a good replica of the gesture they make on the construction site in front of the bench. It also allowed them to take a step back from the risks associated with the use of the crowbar. Being concentrated on their tasks on the construction site and constrained by the pace of the day, they do not have time to wonder about the impact of poor posture or a bad gesture on their health.

Overall, the experiment pleased the professionals. They are aware of the efforts made by the company to protect their health and prevent them from the risk of accidents or

Table 20 Synthesis of novices' comments on the experiment (Group 1)

Positive points	Negative points
– Good experience, I didn't know the construction or the formwork panel, now I know a little more.	– Add representative elements to be able to realize the dimensions of the real formwork panel
– The experience was very good, I learned a lot of things.	– The first question lacks explanations
– It was bluffing. The virtual environment is very immersive.	– The size of my hands in virtual reality was smaller than in reality
– You can feel the effort when you use the crowbar.	– The video lacked information
– I understood how to use the crowbar in the video, and I learned how to do it by using it by myself.	– Some bugs during the experiment
– Good progress in the tutorial	
– Excellent virtual experiment to understand the most used muscles	
– The risks involved in handling the panel during the last step are well understood	

Table 21 Synthesis of professionals' comments on the experimentation (Group 2)

Positive points	Negative points
– I understood the task by watching the video, because in the field I didn't practice a lot the formwork panel.	– Repetitive questionnaire
– I became more aware of the risk to my back and arms when I tried the platform.	– The video does not give all the information
– The game is good. It looked like a real construction site	– The first game (VR Experience) is a bit complicated, you don't understand immediately how to do it
– The experience with the platform and crowbar is better than with the joystick.	
– It's good because it's made to preserve our health.	

occupational illnesses. One participant, however, said that the questionnaire was repeated and that he was annoyed to answer the same questions each time.

5 Conclusion

Tests and a support for discussion were set up on *Virtual Compagnon* with fifteen novices and ten professionals in training. A fifteen questions questionnaire were prepared to evaluate the knowledge of the participants around the panel, the crowbar and the risks related to their uses. This questionnaire was presented to the subjects in four stages. Except for the first questionnaire, all the others were preceded by a training tool: a video, a VR application and the platform *Virtual Compagnon*. The order of presentation of the tools was not randomized to respect the training procedure set up: one theoretical session and one practical session.

Obtained results were statistically analyzed and feedback from the participants were collected.

Both groups had a slightly positive gain. This can lead to the conclusion that there is no rejection of the methodology.

A measure of a form of performance was performed. The test allowed to classify the profiles.

On the one hand, the novices, who learn directly, from the first materials. They understand the context and become familiar with the procedures.

On the other hand, the professionals or expert profiles, who have a solid base of knowledge to start with, and who will have less to learn. That said, the training methodology allows them to take a step back from the way they do things and become aware of the wear and tear that their jobs can cause.

The study also found that regardless of the person's level of background knowledge, the methodology will allow them to learn and progress, regardless of the tool they start with (Video, VR, and Robotic Platform). Each tool provides additional information and complements the other training materials.

The verbatim feedback showed the value of the fun side of the training. The immersion provided by VR allowed professionals to behave naturally because they were in a familiar environment. The integration of the crowbar, and thus a worksite tool, further reinforced this "naturalness" in the professionals' behavior.

The first tests carried out have shown that the methodology results in constant but small gains. These gains are small yet positive. A conclusion can be that the method is validated by the participants and that the targeted population accepts the methodology and does not reject the proposed tools. However, the study must be continued. Indeed, it would be interesting to conduct a study with a larger panel of users and to follow them throughout the training. For the professionals, the lack of homogeneity in the profiles could have influenced the test process. Moreover, the professionals who participated did not have many years of experience in the building industry. It would be interesting to carry out experiments with experienced formworkers.

It would also be interesting to repeat the experiment several times over time. This allows to see the impact of the tool *Virtual Compagnon* in the awareness of the risks related to the task.

Virtual Compagnon is composed of an assistance function. In the first experiments, this contribution were not exploited. It would be interesting to study these assistance modes and observe the participants' behaviors. This would allow to imagine different training scenarios depending on the individual. The trainer would then be able to propose a training content adapted to the basic knowledge level of the trainees. Moreover, the postures were not studied, an important component of the methodology.

It would also be interesting to capitalize on the expertise of experienced formworkers to feed the content of the

method. This would allow to deliver relevant content to the new profiles that join the company.

Acknowledgements We would like to express our special thanks of gratitude to the R&D team of our industrial partner, Bouygues Construction, for the support during this work. We are dearly obliged to thank Bouygues Construction's ergonomists, and all the members of MATFORM and the Gustave Eiffel training center teams for supporting us in this process. At last but not least, we would like to earnestly acknowledge the sincere efforts and valuable time given by the people, the novices and the professionals, who participated in the tests.

Author contributions All authors reviewed the manuscript

Funding Open access funding provided by Université de Versailles Saint-Quentin-en-Yvelines.

Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Beach DS (1965) Personnel: the management of people at work, 2nd edn. Macmillan
- Bhagat KK, Liou WK, Chang CY (2016) A cost-effective interactive 3d virtual reality system applied to military live firing training. *Virtual Reality* 20(2):127–140. <https://doi.org/10.1007/s10055-016-0284-x>
- Bourdakis V (1997) The future of vrml on large urban models. In: The 4th UK VRSIG Conference
- Brown L (2021) Risk management and safety protocols in training. *Safety Sci Rev* 15(2):89–101
- Burdea GC (1999) Haptic feedback for virtual reality. In: *Virtual Reality and Prototyping Workshop*, Laval, France, p 11, <http://www.cai.rutgers.edu/vrlab>
- Burdea GC, Coiffet P (2003) *Virtual reality technology*. John Wiley & Sons Inc, New Jersey
- Burkhardt JM (2003) Réalité virtuelle et ergonomie: quelques apports réciproques. *Le travail humain* 66(1):65. <https://doi.org/10.3917/th.661.0065><http://www.cairn.info/revue-le-travail-humain-2003-1-page-65.htm>

- CNAM (2020) Sinistralité dans le btp : état des lieux | ameli.fr | entreprise. <https://www.ameli.fr/entreprise/sante-travail/votre-secteur/batiment-travaux-publics/chiffres-cles>
- Connolly TM, Boyle EA, MacArthur E, Hainey T, Boyle JM (2012) A systematic literature review of empirical evidence on computer games and serious games. *Comput Educ* 59(2):661–686. <https://doi.org/10.1016/j.compedu.2012.03.004>
- Davis R (2022) Ensuring workplace safety through effective training. Safety Publications
- Dede C (2005) Planning for neomillennial learning styles. *Educause Q* 28(1):7–12
- du Travail M (2019) Plan de développement des compétences. <https://travail-emploi.gouv.fr/>
- Eastman C, Teicholz P, Sacks R, Liston K (2011) BIM handbook: a guide to building information modeling for owners, managers, designers. Wiley, Engineers and Contractors
- Fédération Française du bâtiment (2020) Les chiffres du btp en france. Tech. rep, Fédération Française du bâtiment
- Frisoli A, Salsedo F, Bergamasco M, Rossi B, Carboncini MC (2009) A force-feedback exoskeleton for upper-limb rehabilitation in virtual reality. *Appl Bionics Biomech* 6(2):115–126. <https://doi.org/10.1080/11762320902959250>
- Fuchs P, Moreau G, Berthoz A (2006) Le traité de la réalité virtuelle volume 1: L'homme et l'environnement virtuel
- Ganah A, John GA (2015) Integrating building information modeling and health and safety for onsite construction. *Saf Health Work* 6(1):39–45. <https://doi.org/10.1016/j.shaw.2014.10.002>
- Garrison DR (2011) E-learning in the 21st century: a framework for research and practice. Routledge
- HaiyanXie, Tudoreanu ME, Weishi (2006) Development of a virtual reality safety-training system for construction workers. *Proc 6th Intl Conf Construction Appl Virtual Reality* p 9
- Hakkinen K, Laaksonen M (2011) Safety awareness and psychological factors in construction work. *Saf Sci* 49(1):135–142
- Hales TR, Bernard BP (1996) Epidemiology of work-related musculoskeletal disorders. *Orthop Clin North Am* 27(4):679–709. [https://doi.org/10.1016/S0030-5898\(20\)32117-9](https://doi.org/10.1016/S0030-5898(20)32117-9)
- Health and Safety Executive (2017) Work-related musculoskeletal disorders (wrmsds) statistics in great britain 2017. *Health Saf Executive* 1(1):22
- Hecklau F, Galeitzke M, Flachs S, Kohl H (2016) Holistic approach for human resource management in industry 4.0. *Procedia CIRP* 54:1–6. <https://doi.org/10.1016/j.procir.2016.05.191>
- Hilfert T, Teizer J, König M (2016) First person virtual reality for evaluation and learning of construction site safety. *The International Association for Automation and Robotics in Construction* pp 200–208. <https://doi.org/10.22260/ISARC2016/0025>
- Hollis V, O'Neill J, Turner J (2020) The efficacy of virtual reality simulations for health education: the role of sensory feedback and information. *J Med Internet Res* 22(5):e17155. <https://doi.org/10.2196/17155>
- Jensen MJ, Tolbert AM, Wagner JR, Switzer FS, Finn JW (2011) A customizable automotive steering system with a haptic feedback control strategy for obstacle avoidance notification. *IEEE Trans Veh Technol* 60(9):4208–4216. <https://doi.org/10.1109/TVT.2011.2172472>
- Johnson L, Williams R, Miller T (2019) Integrating theoretical and practical training: a case study in industrial training programs. *Trng Devel Quarterly* 28(4):73–85
- Jones E (2019) The importance of theoretical knowledge in workplace training. *J Trng Devel* 12(4):56–67
- K-Ryole (2020) K-ryole - chariot kross. <https://krossbuilder.fr/>
- Kjeldskov M, Graham C (2019) The role of tactile feedback in virtual reality: Enhancing user awareness and safety in hazardous work environments. *J Occup Health Psychol* 24(1):1–14. <https://doi.org/10.1037/ocp0000112>
- Kolb D (1984) *Experiential learning: experience as the source of learning and development*. Prentice Hall, Englewood Cliffs
- Kozlak M, Kurzeja A, Nawrat A (2013) Virtual reality technology for military and industry training programs. In: Nawrat A, Kuś Z (eds) *Virtual reality technology for military and industry training programs, studies in computational intelligence*, vol 481. Springer International Publishing, Heidelberg, pp 327–334
- Kymmell W (2008) *Building information modeling: planning and managing construction projects with 4D CAD and simulations*. McGraw Hill Professional
- Leborgne (2020) Pince à talon nanovib. <https://www.leborgne.fr/medias2/1/38/f/pince-a-talon-nanovib.pdf>
- López-Arquillos A, Rubio-Romero JC, Gibb AG, Gambatese JA (2014) Safety risk assessment for vertical concrete formwork activities in civil engineering construction. *Work* 49(2):183–192. <https://doi.org/10.3233/WOR-131724>
- Martin H (2016) *Maquette numérique 3d pour la construction : visualiser les connaissances métier et interagir avec des dispositifs immersifs*. Theses, Université Paris-Saclay, <https://tel.archives-ouvertes.fr/tel-01707797>
- Mayer RE (2005) *The Cambridge handbook of multimedia learning*. Cambridge University Press, Cambridge
- Miller J, Smith T (2007) Improving decision-making skills under pressure through virtual environments. *Int J Hum-Comput Interact* 23(5):433–447
- Miller S (2023) Evaluating the effectiveness of passive learning techniques. *Educ Res Q* 18(1):32–47
- Ministère du Travail (2008) Code du travail – article r4541-8. <https://www.legifrance.gouv.fr>
- Nijholt A, Reidsma D (2011) Haptic feedback in virtual reality for training and simulation. In: Association IRM (ed) *Virtual Reality: Concepts, Methodologies, Tools, and Applications*, IGI Global, pp 1166–1187
- OPPBTP (2016) *Troubles musculo-squelettiques (tms)*. <https://www.preventionbtp.fr/Documentation/Explorer-par-produit/Information/Dossiers-prevention/Troubles-musculo-squelettiques-TMS>
- Pappano L (2012) The year of the mooc. *The New York Times* <https://www.nytimes.com/2012/11/04/education/edlife/the-year-of-the-mooc.html>
- Passos C, da Silva MH, Mol ACA, Carvalho PVR (2017) Design of a collaborative virtual environment for training security agents in big events. *Cogn Technol Work* 19(2–3):315–328. <https://doi.org/10.1007/s10111-017-0407-5>
- Patrão B, Menezes P (2013) An immersive system for the training of tower crane operators. In: *Proc - 2013 2nd Experiment@ Intl Conf, exp.at 2013*, pp 158–159. <https://doi.org/10.1109/ExpAt.2013.6703052>
- Pereira AC, Romero F (2017) A review of the meanings and the implications of the industry 4.0 concept. *Procedia Manuf* 13:1206–1214. <https://doi.org/10.1016/j.promfg.2017.09.006>
- Petrova EA, Rasmussen M, Jensen RL, Svidt K (2017) Integrating virtual reality and bim for end-user involvement in building design: a case study. *Lc3 2017* pp 699–709. <https://doi.org/10.24928/JC3-2017/0266>
- Pohlentz P, Gröbe A, Petersik A, von Sternberg N, Pflesser B, Pommer T, Höhne KH, Tiede U, Springer I, Heiland M (2010) Virtual dental surgery as a new educational tool in dental school. *J Cranio-Maxillofacial Surgery* 38(8):560–564. <https://doi.org/10.1016/j.jcms.2010.02.011> <https://linkinghub.elsevier.com/retrieve/pii/S1010518210000363>
- Punnett L, Wegman DH (2004) Work-related musculoskeletal disorders: the epidemiologic evidence and the debate. *J Electromyogr Kinesiol* 14(1):13–23. <https://doi.org/10.1016/j.jelekin.2003.09.015>

- Roy E, Bakr MM, George R (2017) The need for virtual reality simulators in dental education: a review. *Saudi Dental J* 29(2):41–47. <https://doi.org/10.1016/j.sdentj.2017.02.001>
- Sacks R, Aghazadeh F, Bernstein H, Wang G (2013) Construction safety training using augmented reality. *Autom Constr* 32:52–62. <https://doi.org/10.1016/j.autcon.2012.11.004>
- Savall J, Borro D, Gil JJ, Matey L (2002) Description of a haptic system for virtual maintainability in aeronautics. *IEEE Intl Conf Intell Robot Sys* 3:2887–2892. <https://doi.org/10.1109/irfs.2002.1041709>
- Schroeder R (1993) Virtual reality in the real world. history, applications and projections. *Futures* 25(9):963–973. [https://doi.org/10.1016/0016-3287\(93\)90062-X](https://doi.org/10.1016/0016-3287(93)90062-X)
- Schön DA (1987) *Educating the reflective practitioner*. Jossey-Bass, San Francisco
- Sharma A, Haskins M (2015) Real-time feedback in ergonomic training simulations. *J Ergonom* 58(4):281–290
- Smith J (2018) *Training and development in industrial settings*. Industrial Press
- Smith J, Brown A (2021) The impact of practical training on skill retention in industrial settings. *J Appl Train Dev* 35(2):45–59
- Subedi S, Pradhananga N, Carrasquillo A, Lopez F (2017) Virtual reality-based personalized learning environment for repetitive labor-intensive construction tasks. *53rd ASC Annual Intl Conf Proc*
- Tichon J, Diver P (2010) Plant operator simulation: benefits and drawbacks for a construction training organization. *Cogn Technol Work* 12(3):219–229. <https://doi.org/10.1007/s10111-010-0140-9>
- Valero E, Sivanathan A, Bosché F, Abdel-Wahab M (2016) Musculoskeletal disorders in construction: a review and a novel system for activity tracking with body area network. *Appl Ergon* 54:120–130. <https://doi.org/10.1016/j.apergo.2015.11.020>
- Wang P, Becker A, Jones I, Glover A, Benford S, Greenhalgh C, Vloeberghs M (2006) A virtual reality surgery simulation of cutting and retraction in neurosurgery with force-feedback. *Comput Methods Programs Biomed* 84(1):11–18. <https://doi.org/10.1016/j.cmpb.2006.07.006https://linkinghub.elsevier.com/retrieve/pii/S0169260706001647>
- Wang X, Dunston PS, Proctor R, Hou L, So JCY, Chung J, So Y, So JCY (2011) Reflections on using a game engine to develop a virtual training system for construction excavator operators. *Proceedings of the 28th International Symposium on Automation and Robotics in Construction, ISARC 2011* pp 631–636, <https://doi.org/10.22260/ISARC2011/0111>
- Wang X, Li W, Yu X, Akinci B (2018) Critical review of virtual reality applications in construction safety training. *J Constr Eng Manag* 144(3):04017106. [https://doi.org/10.1061/\(ASCE\)CO.1943-7862.20001436](https://doi.org/10.1061/(ASCE)CO.1943-7862.20001436)
- Whyte J, Nikolic D (2018) Augmented and virtual reality in construction. In: *Advances in informatics and computing in civil and construction engineering*, Springer, pp 157–165
- Williams M (2020) Interactive techniques for effective training. In: *Proceedings of the international conference on industrial training*, pp 45–53
- Yousef R, Chatti MA, Schroeder U (2014) Moocs and open education Current state and future directions. *J Educ Tech Soc* 17(1):19–30
- Zaharim NS, Mohamed Z (2020) Virtual reality as a tool for construction safety training in Malaysia. *J Constr Eng Manag* 146(2):04019090
- Zhao D, Lucas J, Thabet W (2009) Using virtual environments to support electrical safety awareness in construction. *Proceedings - Winter Simulation Conference* pp 2679–2690, <https://doi.org/10.1109/WSC.2009.5429258>, <http://ieeexplore.ieee.org/document/5429258/>
- Zhonghua L, Dingfang C, Haoming D, Chenlin S, Zhe L (2008) Research on distributed multi-screen overhead crane simulator. In: *2008 3rd Intl Conf Pervasive Comput Appl, ICPCA08*, vol 2, pp 1003–1006, <https://doi.org/10.1109/ICPCA.2008.4783669>
- Zhou Y, Wang L (2016) Enhancing spatial awareness and hand-eye coordination in virtual reality training. *Virtual Reality* 20(3):215–225
- Zimmermann P (2008) Virtual reality aided design. a survey of the use of vr in automotive industry. In: *Product Engineering*, Springer Netherlands, Dordrecht, pp 277–296

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.