Virtual Reality-based Human Factor Analyses for Ergonomic Improvements in Construction Manufacturing Facilities

by

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ABSTRACT

In construction manufacturing, components (e.g., panels or modules) are produced in a factory environment before being transported and installed in a construction site. In this context, two distinct operational phases are observed: factory, accounting for 60%–90% of the tasks that would typically have been performed on site in conventional construction, and on site, where components are assembled and finishing tasks are completed. Due to the standardization of processes aiming to increase overall facility production, workers in construction manufacturing are often exposed to physical demands (e.g., repetitive motion and awkward body posture) that are associated with the risk of developing work-related musculoskeletal disorders and experiencing physical fatigue, despite the use of semi-automated equipment. Both fatigue and work-related musculoskeletal disorders decrease workers' productivity, motivation, and physical and cognitive abilities. In addition, work-related musculoskeletal disorders are correlated with high absenteeism, increased compensation costs, and early retirements, thus incurring in social and financial losses. Assessing ergonomic risks of workstations and providing preventive measurements such as ergonomic training to workers is thus necessary to not only support a safer workplace and reduce long-term exposure of workers to ergonomic risks associated with fatigue and work-related musculoskeletal disorders, but also improve overall facility production. As research methods to collect human body motions have limitations, such as workplace interruptions and biased results due to subjective observation, this research proposes virtual reality-based ergonomic assessment frameworks to evaluate ergonomic risks and provide real-time ergonomic assessment and postural recommendation during training sessions in a laboratory setting. The proposed frameworks can be applied throughout the design development and operational phases of workstations on a production line. By identifying ergonomic risk ratings proactively in the initial phases of workstation design,

the number of iterations required using physical prototypes is thus reduced, thereby reducing the cost and time required to develop and implement an improved workstation design. In addition, the integration of virtual reality with a motion capture system to provide real-time ergonomic risk assessment and postural recommendations during training on construction manufacturing tasks increases subject's awareness of ergonomically hazardous postures and thus reduces subject's exposure to ergonomic risks in the high-risk range. The proposed frameworks are validated through practical applications with corresponding research experiments that simulate various manufacturing tasks in the construction manufacturing industry. The contribution of the proposed research is innovative virtual reality-based ergonomic risk assessment frameworks capable of providing a robust ergonomic analysis that can be applied for product and process analysis as well as for training on the tasks performed in construction manufacturing facilities.

PREFACE

This thesis is an original work by Regina Celi Dias Ferreira Barkokébas. The research of which this thesis is a part received research ethics approval from the University of Alberta Research Ethics Board, project name "VR-based ergonomic risk assessment in industrialized construction", No. Pro00091088, Dec. 6, 2019. This thesis is organized in a paper-based format, and it follows the University of Alberta's guidelines for a paper-based thesis. Three journal papers and three conference papers associated with the research developed for this thesis have been submitted or published, as follows:

1. **Dias Barkokebas, R.** and Li, X. (2022). "Virtual reality-based real-time postural ergonomic assessment for training of construction manufacturing tasks". *Automation in Construction* (Submitted).

   Chapter 6 of this thesis is composed of this manuscript. I was responsible for the proposed method, data collection and analysis, as well as the manuscript composition. Dr. Li was the supervisory author and was involved with concept formation and manuscript revision.

2. **Dias Barkokebas, R.**, Al-Hussein, M. and Li, X. (2022). "VR–MOCAP-enabled ergonomic risk assessment of workstation prototypes in off-site construction". *Journal of Construction Engineering and Management*, 148(8), 04022064-1– 04022064-17.

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3. **Dias Barkokebas, R.** and Li, X. (2021). "Use of VR to assess the ergonomic risk of industrialized construction tasks". *Journal of Construction Engineering and Management*, 147(3), 04020183.

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5. **Dias Barkokebas, R.**, Al-Hussein, M., and Li, X. "Virtual reality–motion capture-based ergonomic risk assessment of workstation designs of construction manufacturing facilities." In *Proc., CSCE Construction Specialty Conference*, Niagara Falls, ON, Canada (virtual conference), May 26–29.

6. **Barkokebas, R.**, Ritter, C., Sirbu, V., Li, X., and Al-Hussein, M. (2019). "Application of virtual reality in task training in the construction manufacturing industry". In *Proc., ISARC 36th International Symposium on Automation and Robotics in Construction*, Banff, AB, Canada, May 21–24.

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LIST OF ABBREVIATIONS

3D	Three Dimensional
AWCBC	Association of Workers' Compensation Boards of Canada
EMG	Electromyograms
HR	Heart rate
IMU(s)	Inertial Measurement Units
KM	Key Motion
MOCAP	Motion Capture
NASA-TLX	National Aeronautics and Space Administration Task Load Index
NIOSH	National Institute for Occupational Safety and Health
OWAS	Ovako Working-posture Analysing System
PP	Physical Prototype
REBA	Rapid Entire Body Assessment
RR	Respiration Rate
RULA	Rapid Upper Limb Assessment
VR	Virtual Reality
WMSDs	Work-related Musculoskeletal Disorders

CHAPTER 1: INTRODUCTION

1.1. Background and Motivation

In off-site construction, 60%–90% of the tasks conventionally performed on site are instead performed in a factory (Modular Building Institute 2016). Although workers benefit from the factory environment and from the use of automated or semi-automated equipment, they are still exposed to a high degree of physical demand (Public Services Health & Safety Association 2010; Xu et al. 2012). For instance, repetitive motion, which is frequently observed in construction manufacturing tasks due to the standardization of products, intensifies muscular tension, even if awkward body posture is not required and the force level is low (Golabchi et al. 2016; Public Services Health & Safety Association 2010). In fact, forceful exertion, awkward body posture, and repetitive motions are the primary causes of physical fatigue and work-related musculoskeletal disorders (WMSDs) (Canadian Centre for Occupational Health and Safety 2017; Umer et al. 2020), which often result in a loss of physical and cognitive abilities, productivity, and motivation that in turn lead to higher absenteeism and injury rates and early retirement (Botti et al. 2017). It is estimated that WMSDs costs the construction industry approximately $20 billion per year in the United States, primarily in the form of workers' compensation costs (Choi et al. 2022). Given that processes are centralized in workstations on the production line, the extent of worker exposure to the risk of fatigue and WMSDs is largely a function of workstation design. As stated by Deros et al. (2011), a workstation designed by taking ergonomics into account not only promotes the health and safety of workers but also increases the productivity of the production line. Hence, the assessment of human factors and of the ergonomic risks posed to workers at workstations is needed in order to provide a safer workplace and reduce long-term exposure of workers to the risks associated with WMSDs and physical fatigue. Indeed, both human factors and ergonomics focus on the application of psychological and physiological principles to study the relationship between worker and workplace (Health and Safety Executive 2020), so the investigation of this relationship will result in an overall improvement of facility production.

Another essential aspect to be considered in efforts to reduce worker exposure to risks of physical fatigue and WMSDs is worker behaviour, as it is a key determinant in the exposure of workers to avoidable risks (Li et al. 2015). In this regard, two primary factors influence a worker's ability to identify and evaluate risks: experience and training (Sacks et al. 2013). With respect to experience, 25% of the workers injured in the construction industry have less than two months of experience, while workers with two or three months of experience represent just 6% of injured workers (Mučenski et al. 2015). With regard to training, ergonomics training focuses on educating workers on identification of the risk factors responsible for WMSDs, on the proper selection and use of equipment, and on adapting the workstation to their needs (Hoe et al. 2012). However, despite the potential benefits of ergonomics training, according to their recent systematic review of the topic, Faisting and Sato (2019) established that there is no consistent evidence of the impact of providing ergonomic training in terms of reducing physical demand and WMSDs. Their finding underscores the need for further research on this subject.

Traditionally, ergonomic analyses of workplaces are conducted by observing workers on the production line. However, this manual observation requires an ergonomist or a field specialist, and is laborious and error-prone due to observer bias and occlusion issues (Diego-Mas et al. 2015; Guo et al. 2016). Although other methods to collect body motion data for ergonomic analysis purposes are available, there remain significant limitations concerning their practical implementation in construction manufacturing facilities (David 2005). Furthermore, any alteration to workstation design tends to be reactive rather than proactive, resulting in productivity losses and increased time and cost of implementation (Peruzzini et al. 2019). To overcome these limitations, one of the most effective approaches to control the degree to which workers are exposed to the risk of developing WMSDs is to identify and prevent ergonomic risks at the early design stage by using conventional physical prototypes (Jia et al. 2011). However, physical prototyping requires the commitment of major resources (Azizi et al. 2018). Therefore, it is critical to investigate alternative prototyping methods that can be used to rapidly evaluate the ergonomics of a given workstation design or task design and minimize or eliminate iterations with physical prototypes, thus reducing the time and cost required to develop an improved design.

Approaches capable of simulating and virtually modelling working scenarios can achieve a robust analysis of human–product interactions at any stage of design development (Peruzzini et al. 2020). In particular, virtual reality (VR) produces immersive computer-generated virtual environments in which users can experience and provide insights on situations/products found in the real-world (Whyte 2007). VR enables users to review designs based on interactions at a real scale (1:1)—which is one of the primary benefits of physical prototyping—by allowing users to experiment with and evaluate prototypes in a realistic manner (Wolfartsberger 2019). In addition, adjustments to the design of a workstation can be easily incorporated, as an updated design can be quickly re-evaluated in the VR environment (Seth et al. 2011). As such, VR aids in the decision-making process by adding speed and flexibility to the design development phase. The application of VR in the construction industry has been explored from a variety of perspectives, such as engineering and architectural design (Wu et al. 2019; Zhang et al. 2019), training on construction equipment and tasks (Barkokebas et al. 2019; Dhalmahapatra et al. 2021; Joshi et al. 2021; Li et al. 2012), and ergonomic analysis (Battini et al. 2018; Dias Barkokebas et al. 2020; Dias Barkokebas and Li 2020). However, according to a recent systematic review on the subject, research is still needed to realize the full potential of the implementation of VR in the architecture, engineering, and construction sectors (Davila Delgado et al. 2020).

In summary, workers are exposed to ergonomic risks in construction manufacturing facilities due to deficiencies in the workstation design, as well as due to the need to undertake work of a highly physically demanding nature, such as motion repetition. The assessment of ergonomic risks posed at workstations is thus needed to ensure the health and safety of workers, and, consequently, increase the productivity of the production line. However, there remain some deficiencies in the methods used to mimic and anticipate in a laboratory setting the body motions involved in undertaking an entire activity (for the purpose of identifying and reducing ergonomic risks based on real human body motion data). Furthermore, there remains a need to explore the impacts of ergonomics training in terms of reducing physical demands and WMSDs. In this context, VR appears to be an effective method by which to simulate body motions of manufacturing tasks in the construction industry in a controlled and risk-free environment. The integration of VR with a MOCAP system will allow for ergonomic risk in a workplace to be accurately assessed, with the added benefit that it does not disrupt the production line and thereby bypasses the interruptions and productivity losses related to data collection associated with conventional, reactive ergonomics interventions.

In this context, this thesis describes the development of a series of VR-based simulation frameworks culminating in a robust ergonomic analysis framework that can be applied for process analysis as well as for training personnel on the tasks to be performed in construction manufacturing facilities. Through these frameworks, the reliance on physical prototypes can be reduced or eliminated through the simulation of real-world tasks in a virtual/immersive environment, thereby reducing the cost and time required to modify and implement an improved workstation design on the production line. Moreover, in the proposed framework, ergonomic assessment and postural recommendations are embedded in situational training in the context of real-world scenarios powered by the integration of VR and MOCAP technologies. In this way, ergonomics training can be provided with negligible risk and without interfering in overall facility production.

1.2. Hypothesis and Research Objectives

The proposed research is built upon the following hypothesis:

"*Integrating virtual reality (VR) with human factors in a laboratory setting will assist in measuring the ergonomic risks that occur on the construction manufacturing line in order to proactively mitigate them.*"

To verify this hypothesis, this research pursues four objectives (O_x):

O_1: Identify the challenges that need to be addressed in the design of VR experiments to increase their reliability as an ergonomic analysis tool through the investigation, via VR simulation, of the human body motions inherent in construction manufacturing tasks;

O_2: Propose a VR-based ergonomic risk assessment framework to advance the use of VR for ergonomic risk rating analysis relying on traditional manual observation;

O_3: Develop a VR–MOCAP-enabled ergonomic risk assessment framework to provide designers with quantitative and qualitative data on the ergonomic risks inherent in a given design, thereby affording the opportunity for design improvements to be introduced during the prototyping phase of workstation design;

O4: Develop a framework to provide real-time ergonomic risk assessment and postural recommendations during training on construction manufacturing tasks through VR simulation integrated with a MOCAP system in order to improve subject awareness of ergonomically hazardous postures.

As noted above, as the research progresses, the complexity of the VR-based ergonomic risk assessment frameworks increases accordingly, as novel aspects are incorporated into the analysis, thereby providing a simulation approach for robust ergonomic analysis through the integration of innovative technologies—VR, MOCAP, and a wearable physiological monitoring device—as shown in Figure 1.1.

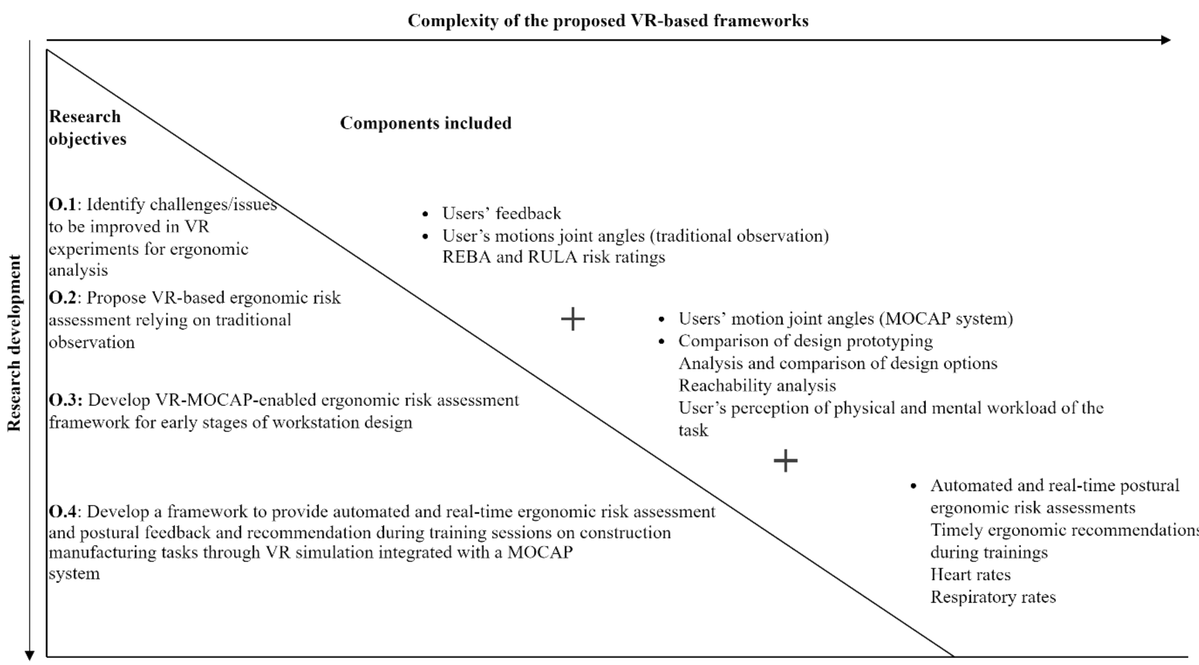

Figure 1.1: Relationship between research development and its complexity.

1.3. Thesis Organization

This thesis is composed of seven chapters. In the present chapter, the background, motivation, hypothesis, and objectives of this research are presented. Chapter 2 provides a review of the existing literature on the topics relevant to the research presented in this thesis. As such, it encompasses information on the methods used for collecting body motion data, including the strengths and limitations of existing methods, as well as information on existing ergonomic risk assessment tools, and on the main contributions of VR applications in ergonomic risk assessment and training on construction tasks.

Chapter 3 investigates the implementation of VR for ergonomic assessment of workstation design in construction manufacturing, focusing on human body motions. By carrying out a pilot test of the proposed research experiment, the challenges to be improved in the research experiment are identified in order to increase the reliability of the proposed VR simulation for ergonomic analysis (O_1). An existing rule-based ergonomic risk evaluation method, Rapid Upper Limb Assessment (RULA), is used to evaluate postural ergonomic risks.

In Chapter 4, a VR-based ergonomic assessment method is proposed by which to investigate the human body motions associated with a given construction manufacturing task, and its accuracy is verified through a practical application. The proposed method builds upon the results of the pilot test presented in Chapter 3. In the practical application presented in Chapter 4, frame-by-frame observation of real participants is the method used to acquire information on human body motions, and two existing rule-based ergonomic risk evaluation methods—RULA and Rapid Entire Body Assessment (REBA)—are used to evaluate postural ergonomic risks (O_2).

Chapter 5 presents a VR–MOCAP-enabled ergonomic assessment method by which to evaluate ergonomic risks in a laboratory setting during the design phase of workstation development (O_3). The use of wearable MOCAP sensors to collect body motion data is incorporated to the method proposed in this chapter; as such, an additional layer of complexity and accuracy is added in relation to the method presented in Chapter 4. Ergonomic assessments are conducted in the form of assessment of postural ergonomic risks (i.e., deployment of RULA and REBA), reachability analysis, and evaluation—using the NASA Task Load Index (NASA-TLX)—of the subject's perception of the physical and metal workload of a given task.

In Chapter 6, a method by which to provide ergonomic risk assessment and real-time postural recommendations during training on construction manufacturing tasks through the integration of VR simulation, a MOCAP system, and a wearable physiological monitoring device (O_4) is proposed. For this purpose, RULA and REBA are used to evaluate postural ergonomic risks in real time, physiological measurements such as heart and breathing rates are collected for the purpose of physical fatigue and workload analysis, and a questionnaire is administered to solicit feedback on subjects' perceptions of the VR simulation, and particularly of the task's physical and mental workload (using the NASA-TLX). A pre-test/post-test procedure with a randomized control group research is conducted to verify the effectiveness of ergonomics training based on empirical evidence.

Finally, Chapter 7 summarizes the conclusions, contributions, and limitations of this research, and provides recommendations for future work.

CHAPTER 2: LITERATURE REVIEW

In this chapter, existing methods for body motion data collection and existing ergonomic risk assessment tools are reviewed. In addition, prior research studies focusing on applications of VR to ergonomic risk assessments are reviewed in order to verify gaps in the existing literature relevant to the research presented in this thesis.

2.1. Body Motion Data Collection

Several methods are available for collecting body motion data for ergonomic analysis purposes; however, there remain some notable limitations concerning their real-life implementation in construction manufacturing (David 2005; Li and Buckle 1999). To evaluate potential risks that workers may encounter in the workplace, pertinent information, such as body joint angles, needs to be acquired accurately and efficiently, but this can be time-consuming and error-prone, depending on the chosen method of data collection (Li et al. 2018). The majority of existing ergonomic risk analysis methods can be classified as either self-report, observational, physiological measurements (i.e., direct, indirect, digital, and biomechanical), or digital, as summarized in Table 2.1. Self-report involves the use of questionnaires, interviews, and diaries (Li et al. 2018). Observational methods collect detailed physical data either based on subject observation (whether directly on site or by viewing recorded video footage) or based on post-analysis of worker behaviours (Roman-Liu 2014). Physiological measurements focus on body joint angles, force loads, muscle activity, etc. Direct-based physiological measurements, such as motion capture (MOCAP) systems, acquire body motions in real time using sensors or markers that are attached to the human body (Bortolini et al. 2018). There are two primary types of MOCAP systems: optical and non-optical. Optical MOCAP systems are composed of markers and multiple cameras; as they rely on video cameras capturing the positioning of sensors, these systems are susceptible to obstruction due to operational motions (Bortolini et al. 2018). Non-optical systems such as inertia systems are composed of small inertial measurement units (IMUs) that use a gyroscope, magnetometer, and accelerometer to estimate body movements without the need for a visual field (Fletcher et al. 2018). Due to their wireless communication capability, moreover, inertial MOCAPs are portable (as long as the sensors are within the wireless range). Indirect measurements, in contrast, use computer-vision methods and Kinect range camera to collect body motions (Ray and Teizer 2012). Biomechanical analysis, meanwhile, uses computer software to perform the analysis based on the prediction of the subject's reach, strength, metabolic rate, and the time needed to finish the given task (Feyen et al. 2000). Alternatively, digital measurement derives body motion data from 3D animations generated to represent real-world tasks (Li et al. 2018). In light of the limitations of these methods as summarized in Table 2.1 and as pointed out by Wang et al. (2015), there is still an opportunity to identify an effective alternative for collecting body motion data for ergonomic risk analysis purposes in a controlled environment (such as a laboratory setting) in which human–product interactions can be simulated without causing interruptions to the real workplace.

VR has garnered attention in recent years as a viable alternative for mimicking the real environment in a laboratory setting, since it allows users to interact in, manipulate, and explore 3D environments in real time and at a real scale (Sampaio et al. 2010). The present study thus aims to advance the integration of VR and MOCAP systems by proposing a method by which to assess the ergonomic risks associated with construction manufacturing tasks based on real motion data and in a laboratory setting, thereby reducing work interruptions. The proposed VR–MOCAP-based method allows for the acquisition of body motion data with a high degree of accuracy since results are built on precise sensor data, thus avoiding the inter-rated discrepancies encountered in observational methods.

Table 2.1: Comparison of methods for collecting body motion data (adapted from Wang et al. 2015 and Li et al. 2018).

		Methods [example]					
		Self-report [questionnaire, interview, body map]	**Observation** [direct and indirect observation]	**Direct measurements** [MOCAP systems]	**Indirect measurements** [computer-vision, Kinect]	**Biomechanical** [computer software]	**Digital measurements** [3D models]
Focus of analysis	Entire body		■	■	■	■	■
	Upper limbs		■			■	■
	Specific body part	■				■	
	Body posture			■	■		
Limitations	Time consuming	■	■		■**		■
	Biased results	■	■				
	Inter-rated discrepancy	■	■				
	High cost			■			
	Occlusion & Illumination			■*	■		
	Distance				■		

	Technical support			■	■		
	Motion data required					■	■
	3D modelling skills						■
	Rigid body					■	

Note: *Applicable only for optical sensors. **Time-consuming post-analysis.

2.2. Ergonomic risk assessment methods

Rapid Entire Body Assessment (REBA) (Hignett and McAtamney 2000) and Rapid Upper Limb Assessment (RULA) (McAtamney and Corlett 1993) are not only widely used in research studies, but are also popular within industry and considered to be reliable assessment tools (Kong et al. 2018). They provide a quantitative risk score based on a subject's posture that, in turn, is associated with a qualitative risk rating. While RULA focuses predominantly on the upper body, REBA focuses on the entire body and thus includes the joint angles of legs in its assessment. Although the primary criterion in both RULA and REBA assessments is the body posture, which is measured by assigning sub-scores for each body segment based on ranges of joint angles, both methods also consider the required muscle force, coupling conditions, and the frequency of the posture in calculating the total score (Hignett and McAtamney 2000; McAtamney and Corlett 1993). As such, these assessment methods are capable of detecting the primary causes of WMSDs in construction manufacturing tasks. Both RULA and REBA are applied for postural ergonomic risk assessment in the approach proposed in this thesis. A notable challenge with regard to the deployment of RULA and REBA assessments is the fact they require accurate joint angle information as a key input, and this can be difficult to obtain using traditional observation of subjects in their working environment (Nayak and Kim 2021).

2.3. Virtual Reality Applied to Ergonomic Risk Assessment

Virtual reality (VR) is defined as a simulation in which, through the generation of immersive virtual environments, users can experience, and provide unique insights on, real-world elements, projects, and activities. (Whyte 2007). VR allows users to manipulate, interact in, and explore 3D environments in real time by providing a representational fidelity of the real-world, a feeling of presence and immersion, and a high level of engagement (Sampaio et al. 2010). In terms of industrial applications, VR facilitates virtual prototyping by allowing users to evaluate prototypes in a realistic manner during early design development (Wolfartsberger 2019). Furthermore, the use of VR during early design phases allows for setups to be easily modified, and also enables design reviews based on participant interaction with the project at a real scale (1:1), which would typically occur only at a later stage using physical prototypes. As such, VR aids in the decision-making process. Seth et al. (2011) state that the use of VR is an ideal way to simulate assembly activities, since this requires regular and intuitive manual interaction; in this respect, VR is positioned as a supporting technology capable of overcoming the disadvantages of physical prototyping, which entails the allocation of significant resources and time to modify an existing prototype, as VR enables the assessment of ergonomic risks even during the early design phase of workstations and production lines.

As depicted in Table 2.2, the integration of existing ergonomic assessment methods—i.e., REBA and/or RULA—with VR and MOCAP to analyze risks in manufacturing tasks has been investigated in a number of studies. As noted, though, relatively few studies have investigated the application of VR to ergonomic analysis in a factory environment; moreover, those that are available tend not to focus on the construction manufacturing industry (please refer to the "engineering field" columns in Table 2.2). In addition, these existing studies have either use mixed prototyping to conduct the analyses (Bruno et al. 2020; Peruzzini et al. 2019; Vosniakos et al. 2017); used an existing computer software tool such as DELMIA Ergonomics or Siemens Jack to calculate RULA scores (Azizi et al. 2018; Peruzzini et al. 2019; Wang et al. 2022); used a questionnaire/checklist (Aromaa and Väänänen 2016); conducted experiments either in the factory to validate the design of a virtual workstation (Caputo et al. 2018a; b) or entirely in a virtual environment in which both workers and tasks are virtual elements (Azizi et al. 2018); focused primarily on the investigation of fatigue in VR (Azizi et al. 2018); derived information on human body motion (i.e., estimation of joint angles) based on the frame-by-frame observation of a video recorded in Unity 3D software (Vosniakos et al. 2017); or proposed a theoretical methodology in which application and effectiveness is not demonstrated through a substantial case study—e.g., Battini et al. (2018), Manghisi et al. (2022), and Simonetto et al. (2022). Peruzzini et al. (2016) propose a protocol analysis for the assessment of industrial workstations in which both RULA and REBA are recommended as units of measurements for ergonomic analysis. (Both methods, RULA and REBA, are used as part of the ergonomic risk assessment conducted in the research presented in this thesis.) Pontonnier et al. (2014) state that ergonomic studies of assembly tasks using VR still require further investigation. Indeed, after reviewing the existing literature on the application of VR to ergonomic analysis specifically with regard to worker interactions with the workplace, Silva et al. (2020) suggest that further research is required to explore how VR can support ergonomic analysis in specific tasks (including during product development phase). The conclusions of Pontonnier et al. (2014) and Silva et al. (2020) indicate that there are opportunities for future research on this topic.

Table 2.2: Comparison of previous studies exploring the integration of VR and MOCAP for ergonomic analysis.

Reference	Engineering field				MOCAP system			Ergonomic analysis				
	Industrial	Mining	Aero-space	Auto-motive	D-O	D-I	I-K	RULA	REBA	Self-report	Posture	Other
Pontonnier et al. (2014)	■				■			■				■ Muscle Activity
Aromaa and Väänänen (2016)		■			■					■		
Vosniakos et al. (2017)			■				■	■	■	■		
Azizi et al. (2018)	■							■				
Caputo et al. (2018a)				■		■					■	■ EAWS
Caputo et al. (2018b)				■		■					■	■ EAWS
Battini et al. (2018)	■					■						
Rizzuto et al. (2019)					■						■	■ Fingertip velocity
Peruzzini et al. (2019)	■				■			■				
Bruno et al. (2020)				■	■			■				

Wang et al. (2022)	■				■							
Manghisi et al. (2022)	■						■	■				
Simonetto et al. (2022)	■					■			■			

Note: abbreviations used in the table: D-O: Direct measurement-Optical | D-I: Direct measurement-Inertia | I-K: Indirect measurement-Kinect | EAWS: European Assessment Worksheet.

The use of VR integrated with MOCAP to provide situational training with real-time ergonomic assessment and postural recommendations is a beneficial approach in that it provides a learning-by-doing experience with reduced risks and with no interference in the production line (Barkokebas et al. 2019; Joshi et al. 2021), as well as motivating and stimulating subjects to better understand real-life tasks (Pan et al. 2007). Ojelade and Paige (2020) explore the use of VR for training of construction workers, focusing on teaching subjects how to perform certain tasks (i.e., lifting, material handling, and arrangement of items) with less ergonomic risk based on the National Institute for Occupational Safety and Health (NIOSH) equations. Another recent study proposes a protocol for analyzing cognitive load during VR training sessions focusing on the assembly of agricultural vehicles (Brunzini et al. 2021). However, in these studies, the ergonomic analyses are not performed in real time. As such, there is a need for a real-time ergonomic assessment which allows for ergonomics recommendations to be made available to subjects based on their own body motions while they are receiving training in a VR simulation.

As the preceding discussion demonstrates, there is still a need for a method by which holistic ergonomic analysis with rich interactions (e.g., motion, physiological measurements, and reachability) can be conducted using VR, particularly with regard to the analysis of construction manufacturing tasks. The frameworks proposed in the present research can be applied from the workstation design development phase through to training on construction manufacturing tasks, thereby improving workstation ergonomics and reducing the incidence of unsafe worker behaviour by integrating ergonomics recommendations in the training sessions. Ultimately, the proposed frameworks are presented as an alternative tool for evaluating design options and operational tasks based on real motion data to improve workplace ergonomics and worker behaviour, thereby reducing injury rates and helping to mitigate the risk of developing a WMSD.

CHAPTER 3: APPLICATION OF VIRTUAL REALITY TO PERFORM ERGONOMIC RISK ASSESSMENT IN INDUSTRIALIZED CONSTRUCTION: EXPERIMENT DESIGN[1]

3.1. Introduction

In recent years, the construction industry in Canada ranked among the top four industries with the highest number of diseases, lost time injuries, and fatalities (AWCBC 2019). Furthermore, three of the primary causes of work-related musculoskeletal disorders (WMSDs) (awkward body posture, forceful exertion, and repetition motion) are often encountered by workers of construction industry (PSHSA 2010). Studies identify that WMSDs lead to higher absenteeism and injury rates thus resulting in significant productivity losses (Botti et al. 2017). According to Brinzer and Banerjee (2017), workers' performance, which is affected by workers' individual skills to complete a task and the workplace's ergonomic conditions, significantly affects the overall performance of a production system. The investigation of human body motion in manual handling operational tasks in industrialized construction is thus needed to identify hazardous working pattern, minimize WMSDs, and improve overall system performance.

Traditionally, information with respect to workers' body posture is acquired manually by observing activities on site, watching recorded videos, and/or using a questionnaire (Zhang et al. 2018). Focusing on two main factors, body posture and biomechanical analysis, several approaches have been developed to identify and evaluate ergonomic risks (Golabchi et al. 2016). Rapid Entire

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[1] The manuscript appearing as Chapter 3 of this thesis is published as Barkokebas, R., Ritter, C., Li, X., and Al-Hussein, M. (2020). "Application of virtual reality to perform ergonomic risk assessment in industrialized construction: experiment design". In *Proc., ASCE Construction Research Congress (CRC)*, Tempe, AZ, USA, Mar. 8–10.

Body Assessment (REBA) (Hignett and McAtamney 2000), Rapid Upper Limb Assessment (RULA) (McAtamney and Corlett 1993), and Ovako Working Posture Analysing System (OWAS) (Karhu et al. 1977) focus on body posture; while 3D Static Strength Prediction Program and OpenSim use biomechanical analysis. To apply RULA and REBA, which are often used in research studies, information on upper and lower arm, wrist, neck, trunk, legs, and force loads is required as input. Based on predefined rules, which focus primarily on body joint angles and weight of objects being lifted, a score associated with a risk level is obtained (Li 2017; Golabchi et al. 2018; McAtamney and Corlett 1993).

In industrialized construction, workstation design and factory layout have a significant impact on workers' exposure to awkward body postures, forceful exertion, and repetitive motion (Michalos et al. 2018). Assessing ergonomic risks during the design phase of workstations is thus essential to minimize risks. However, conventional methods of prototyping (e.g., mock-ups) are costly and time-consuming (Karkee et al. 2011). Virtual reality (VR), defined as the generation of immersive environments from which one can virtually perform a task that represents an existing task in the real-world (Whyte 2007), is found to be an alternative solution to overcoming these prototyping challenges (Lawson et al. 2016). In order to develop VR applications, detailed information is obtained for the task being simulated, 3D elements are modelled based on this information, and then 3D visualizations and user interactions are generated by a game script designed using game engine software (Wolfartsberger 2019). Due to its visualization capabilities, VR eases decision-making processes, especially during the design phases, as it facilitates communication between different stakeholders (Sampaio et al. 2010). Studies explore VR applications in the construction industry with emphasis on several areas such as safety hazard detection (Albert et al. 2014; Guo et al. 2012; Zhao and Lucas 2015), virtual prototyping (Huang et al. 2007; Li et al. 2012), and ergonomic analysis (Han et al. 2011; Inyang et al. 2012). Although there are studies focusing on VR applied to ergonomic analysis in the construction industry, the majority of studies in this area focus on the manufacturing (Caputo et al. 2018; Peruzzini et al. 2019) and industrial industries (Battini et al. 2018; Peruzzini et al. 2017).

In light of the information provided, the objective of this study is to investigate the implementation of VR to ergonomically assess the design of workstations developed for industrialized construction with a focus on the assessment of human body motions.

3.2. Methodology

This paper is the first phase of a larger study that aims to explore the application of VR to perform ergonomic risk assessment in industrialized construction. In this context, the objective of this phase is to validate and identify challenges/issues to be improved in the design of the VR experiment to increase its reliability in terms of ergonomic analysis. Figure 3.1 shows the methodology used to test the experiment.

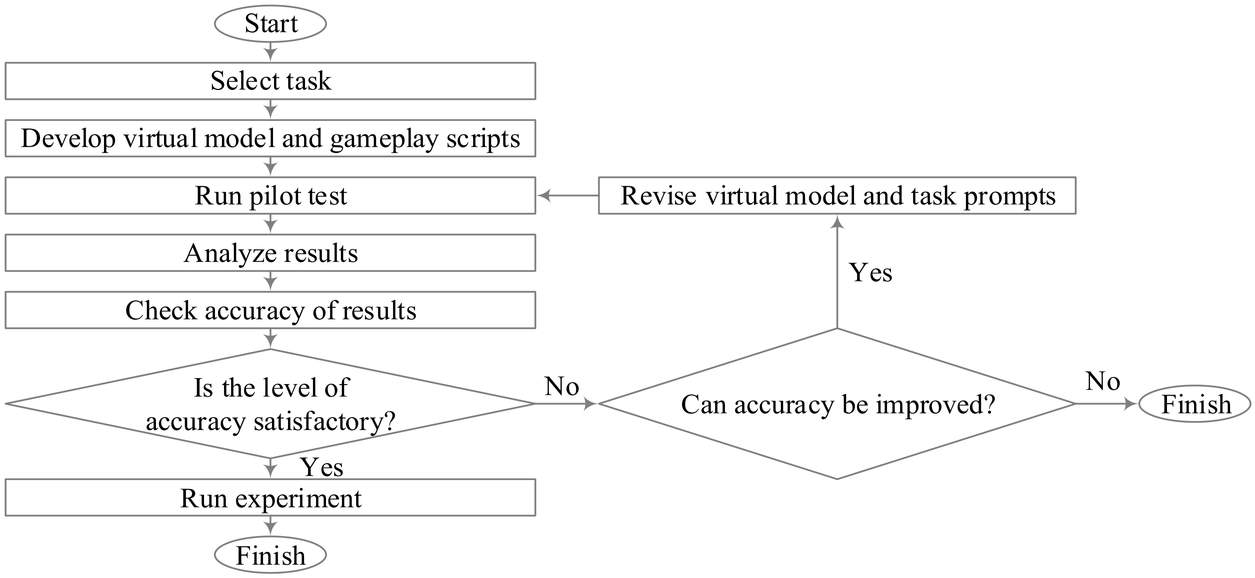


Figure 3.1: Methodology used for testing the design of the VR experiment.

To achieve the objective of this study, information on the task to be simulated (e.g., sequence of activities and tools required), production line layout (e.g., position of workstations and sequence of activities), and workstation design (e.g., height, length, and width) is required to design the virtual environment used in the VR application. In terms of users, two pieces of information are collected: (a) general information such as gender and age, and (b) body movements (i.e., joint angles), which are obtained by observing videos recorded during the VR experiment. Once the user completes the VR experiment, his/her body posture is analyzed, and the RULA scores are calculated. RULA is selected as the ergonomic assessment tool since the task simulated in this study mostly requires movements of the upper limbs, which are covered by RULA (McAtamney and Corlett 1993). Identification of improvements for the design of the VR experiment, verification of the suitability of the developed VR experiment, and RULA scores of the simulated task are the outputs of this study. A summary of the research methodology followed in this study is illustrated in Figure 3.2.

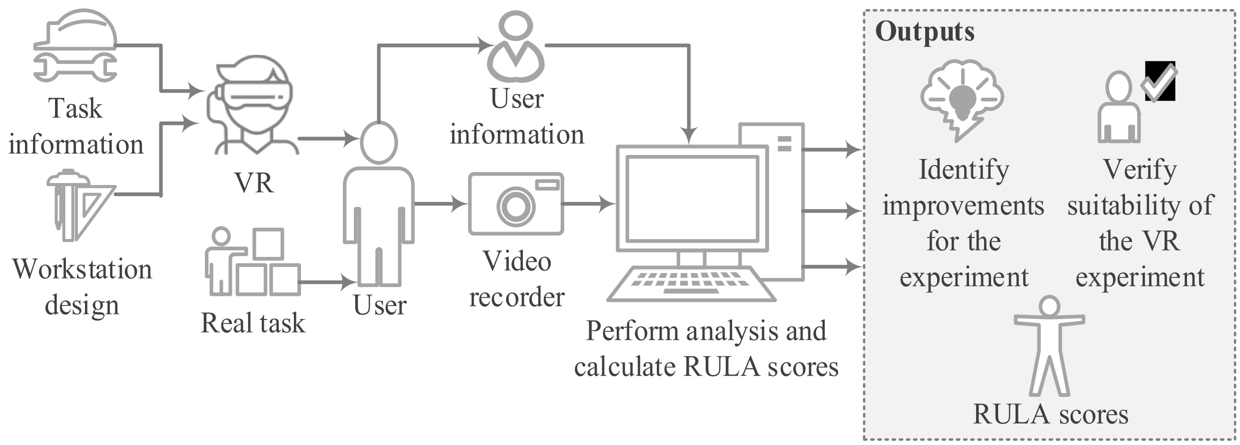


Figure 3.2: Overview of research methodology.

It is important to mention that this research is an extension of the study conducted by Barkokebas et al. (2019), which explores the design and verification of a VR experiment developed to assess how two training techniques—VR experiment and a printed instructional manual—affect the performance of a user conducting a maintenance task. Challenges and issues related to the users' VR experience identified in the mentioned study are addressed herein. In addition, the VR experiment used in Barkokebas et al. (2019) is modified to adapt the VR application to the needs associated with ergonomic risk assessment.

3.2.1. Experimental Design and Hypothesis

This study is built upon the hypothesis that virtual reality applied to perform human body analysis could assist in identifying ergonomic risks accurately in manual handling operational tasks in industrialized construction in a safe and controlled environment without the need of developing real mock-ups. In order to explore this hypothesis, a VR experiment is designed and tested to verify its suitability for ergonomic analysis as well as to identify areas of design improvement. Since the primary objective of the VR experiment is to perform ergonomic analysis, its design needs to take into consideration how the task is performed in a real environment such that the VR application properly mimics the task virtually. To address this, before creating 3D models and gameplay scripts for the VR application, the authors not only observed the task being conducted in a real environment, but also performed the task themselves. By doing so, a comprehensive assessment of the task was acquired enabling the authors to validate 3D models and scripts during their development.

The task simulated in the VR application consists of a sequence of subtasks required to disassemble the drilling area of a wood framing machine in order to perform its maintenance. As observed in Figure 3.3, the task requires the user to use both his/her hands and different tools to move pieces of equipment. Although pieces of machinery need to be lifted, their weights do not exceed two kilograms, therefore, the weight does not have an impact on RULA scores (McAtamney and Corlett 1993). To compare the RULA scores obtained using the VR experiment with those obtained in a real environment, a participant is asked to perform the same task in both environments.

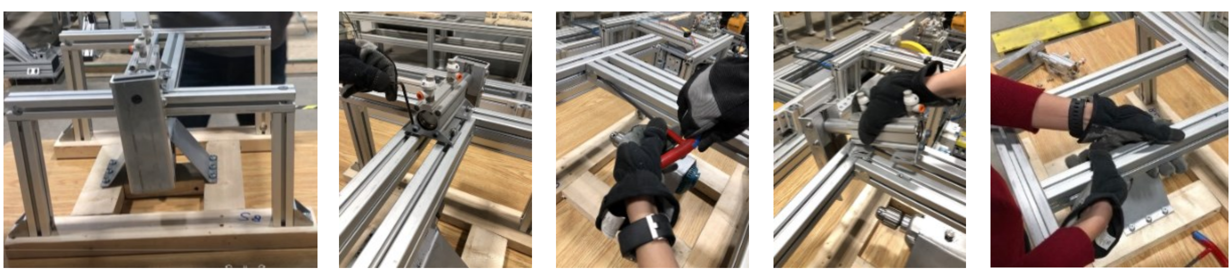
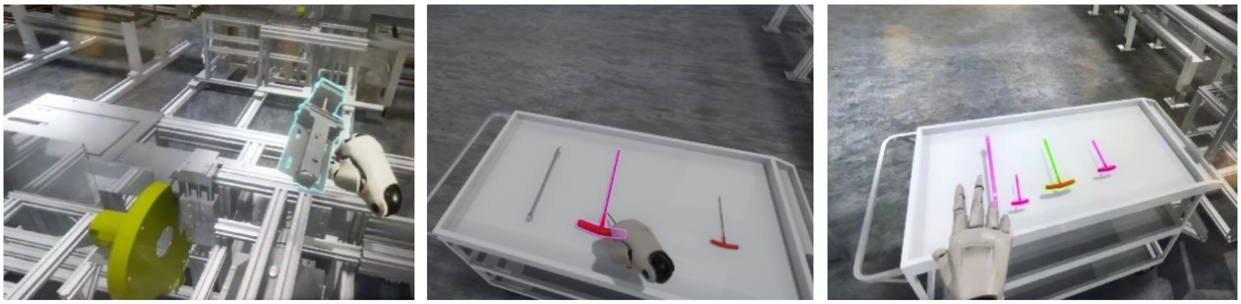


Figure 3.3: Examples of subtasks required to complete the task simulated in the VR experiment.

3.2.2. Virtual Reality Design

Unreal Engine is chosen as the game engine used to develop the VR application as it has a more user-friendly interface, compared to Unity Engine, and it enables the use of Blueprint Visual Scripting to develop VR interactivity. Autodesk 3ds Max and Photoshop are used to create assets. The VR equipment used is an HTC VIVE system, which includes headset, hand controllers, and base stations. Since the VR application represents a machine developed by the same research group as the authors, SOLIDWORKS files of the real-life machine are used to build its virtual model in an accurate manner.

To address one of the issues identified in Barkokebas et al. (2019), the user not being able to observe one's body in the virtual experiment, a virtual hand is introduced in the gameplay script and 3D modelling developed for this study. As a result, users can see how commands triggered using the hand controllers interact with the virtual environment. In addition, the virtual hands also allow the user to better understand reach/movement of his/her hands and arms. Aiming to enhance the representation of a real task in a VR application, user interactions with tools and objectives are also improved based on the findings of Barkokebas et al. (2019). For instance, when a subtask requires the user to hold part of the equipment with his/her hands, this action can be seen in the VR environment (Figure 3.4a); also, if the user completes a subtask with a tool and another one is required, one needs to release the current tool in order to hold another (Figure 3.4b).



a. Visualizations of virtual hand | b. Constraints added to the VR application | c. Instructions on tasks are given to participants

Figure 3.4: Examples of user interactions in the VR environment.

By highlighting the tools and piece of equipment that the user should work on, instructions on tasks to be done and tools to be picked are provided to the user inside the VR experiment (Figure 3.4c). The gameplay script of the VR application is designed in such a way that the user cannot do a subtask that is out of sequence. Similarly, if a wrong tool is picked up, the application does not allow the user to proceed until he/she selects the correct tool. The user is notified of his/her progress via a tag shown inside the VR application.

3.2.3. Participants

To assess the experiment, a pilot test is run with four people (two males and two females). All participants are part of the same research group as the authors; undergraduate and doctoral students who have an engineering background, have experienced VR before, and are between 24 and 30 years old. Further information on participants is summarized in Table 3.1. Prior to participating in the experiment, participants receive an overview of the task to be performed, and instructions on how to use the hand controllers. Participants are also notified that they are being video recorded.

One participant among the four is also asked to complete the task in a real environment to assist with the validation of the RULA results obtained with the proposed VR experiment.

Table 3.1: Information on participants.

Participant	Gender	Height (cm)	Weight (kg)	Historical injury
#1	Female	163	55	No
#2	Male	171	78	No
#3	Female	165	60	No
#4	Male	190	100	No

3.2.4. Data Collection and Analysis

The pilot test of the experiment is carried out in a 2.45 m × 2.45 m VR lab located in a research facility. In this VR lab, participants can move safely within the borders of the VR system. In addition to the VR system, there are one 75″ TV, two tables, a computer to run the VR experiment, and video recording equipment. Participants receive one minute to explore the VR application developed in this study to get familiar with its interface, hand controllers, and its scenario. After this time, it is verified whether the user is willing to continue with the experiment. Once users agree to continue, video recording devices are set, and the pilot test begins.

To calculate RULA scores, a few assumptions are made. The task is divided into eight subtasks. Video recording is selected as the approach to obtain information on user's posture and motion since it is a cost-effective approach that does not disrupt users during data collection (Li and Buckle 1999). By analyzing the video of each participant, RULA scores are calculated for each of the eight subtasks. It is important to clarify that the worst scenario is assumed for the RULA score—

i.e., by watching the video, authors identify the body posture with the higher ergonomic risk and select it to conduct the score calculation.

3.3. Results

By observing the videos recorded during the pilot test, RULA scores are determined as shown in Table 3.2. It is noted that the majority of the scores obtained with the VR experiment fall within the same risk level (Table 3.3). Significant discrepancies are identified in Subtask 4, 7, and 8. In Subtask 4, the primary difference in terms of body posture is the angle of the lower arms. The neck position is the factor that affected the RULA scores of Subtask 7. Subtask 8 requires the participant to remove the drill from the machine; it is identified that the scores varied due to neck position. A couple of participants kept their neck angles between 20° and 30°, and also rotated their neck instead of rotating their entire body to release the drill on the table. Figure 3.5 contains samples of body movements used to perform the RULA analysis. Based on the interpretation of RULA scores (Table 3.3), the subtasks investigated in this study have a low ergonomic risk thus changes may be needed, but they are not pressing.

Table 3.2. RULA scores.

Subtask number	Subtask description	RULA score of participants - VR				RULA score - Real
		#1	#2	#3	#4	#4
Subtask 1	Remove screws from drilling clamp	3	3	4	3	3
Subtask 2	Remove drilling clamp	3	3	3	3	2
Subtask 3	Loosen supporting bars	4	3	3	4	3
Subtask 4	Remove supporting bars	3	3	2	3	NA[1]
Subtask 5	Remove side screws from drilling case	4	4	3	4	3
Subtask 6	Remove central bolt that attaches drill to drilling case	4	3	3	3	3
Subtask 7	Remove drilling case	2	3	2	3	4
Subtask 8	Remove drill	2	4	4	2	NA[2]

[1] In the real environment, the participant moved the bars to the side and did not remove them from the machine.

[2] The drill is attached to the structural part of the machine and thus cannot be removed in the real environment.

Table 3.3. Interpretation of RULA scores (McAtamney and Corlett 1993).

RULA score	Risk level	Action required
1–2	Negligible risk	No action required
3–4	Low risk	Change may be needed
5–6	Medium risk	Further investigation is required, change should be done soon
6+	Very high risk	Implement change now

Figure 3.5. Samples of body movements used to perform the RULA analysis.

By comparing the RULA scores obtained in the VR experiment with those obtained in a real environment, it is verified that the VR experiment represented the reality to the extent that ergonomic risks are identified accurately. As observed in Table 3.2, ergonomic risks are classified in the same risk level whether they were observed in the VR experiment or the real environment, with exception of Subtask 2, which represents the removal of the drilling clamp (refer to Figure 3.4a). It is verified that in the VR environment, the participant keeps looking down while holding the piece of equipment and thus his neck angle is between 20° and 30°, which in the real environment does not occur. Additionally, in the real environment, participants' wrists are slightly angled to the sides, which also affected the RULA score. Although Subtask 2 is classified in a dissimilar risk level, the calculated scores are not significantly different—they vary by only one point. It is noted that increasing the complexity of the task to include more body demanding movements, such as bending and overreaching, could increase the level of detail of the VR application and thus increase the risk of discrepancies in terms of ergonomic risk assessment. However, for manual handling operational tasks similar to the one investigated in this study, the VR experiment is considered suitable for performing ergonomic analysis.

3.4. Limitations and Future Work

Running a pilot test allowed for the identification of key parameters to be improved for the next phase of this study. It is noted that the body movements demanded in the task simulated in this study do not vary significantly throughout the experiment, which may have facilitated the collection of body angles. In addition, interaction between both hands, and hands and tools needs to be improved to reduce the gap between actions performed in the virtual and the real environment. For instance, a discrepancy is noted between the body movements required to loosen the screws in the real environment and the virtual experiment. Although this discrepancy did not affect the calculated RULA scores, this issue should be addressed in future studies.

Additionally, the complexity of the task will be increased in the future to account for tasks that are more demanding for the human body. The integration of VR with a motion capture system is also indicated as a future direction of study with the objective of automating and enhancing the accuracy of information on body angles. Furthermore, this pilot test was run with a small group of participants, which limits the generalization of its results. The study will be expanded in the future to address this limitation.

3.5. Conclusion

This study validates the design of a VR experiment to conduct ergonomic risk analysis; also, it identifies challenges/issues to be improved in the virtual environment to increase its suitability for performing ergonomic studies. Based on the pilot study performed, it is concluded that the proposed VR experiment is suitable to perform ergonomic analysis. A couple of improvements to the VR application is also identified such as increasing the complexity of the task and enhancing the interactions between virtual hands and tools aiming to further enhance ergonomic risk assessments.

3.6. Acknowledgements

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CHAPTER 4: USE OF VIRTUAL TO ASSESS THE ERGONOMIC RISK OF INDUSTRIALIZED CONSTRUCTION TASKS[2]

4.1. Introduction

In off-site construction, construction components (e.g., modules and panels) are produced in a controlled factory environment prior to being transported and installed on site (Liu et al. 2019). In this context, two operational phases are identified: (a) factory, which accounts for 60%–90% of the tasks that would typically have been performed on site in conventional construction, and (b) on site, where industrialized components are assembled and finishing tasks are completed (Modular Building Institute 2016). Industrialized construction entails standardization of products and processes, supported by continuous improvement principles, with the underlying aim of reducing the complexity of construction and increasing productivity (Bertelsen 2004). To standardize products, researchers have proposed a further breakdown of construction components into constituent elements to be produced in the factory environment, which can lead to an increase in physical workload and motion repetition, despite the use of automated equipment (Botti et al. 2017; Mossa et al. 2016); while process standardization has been proposed as a strategy encompassing the development of procedures to account for the distinctive aspects of the construction industry (Yu et al. 2013). As a result, superior quality products, reduced waste, increased productivity, and a consistent working schedule in comparison with traditional on-site construction are achieved (Modular Building Institute 2016; National Association of Home Builders 2019).

[2] The manuscript appearing as Chapter 4 of this thesis is published as Dias Barkokebas, R. and Li, X. (2021). "Use of VR to assess the ergonomic risk of industrialized construction tasks". *Journal of Construction Engineering and Management*, 147(3), 04020183.

Although industrialized construction carries the above-mentioned benefits, improvements in terms of safety and ergonomics are still needed. According to the Association of Workers' Compensation Boards of Canada (AWCBC 2019), the construction industry accounted for the fourth-highest number of diseases and lost-time injuries, and the highest number of fatalities, among all industries in Canada. Moreover, construction workers are often exposed to working conditions that impose higher physical demands, compared to other industries, such as forceful exertion, awkward body posture, and repetitive motion (Public Services Health & Safety Association 2010; Wang et al. 2015); these physical demands are primary causes of work-related musculoskeletal disorders (WMSDs) (Canadian Centre for Occupational Health and Safety 2017). For instance, repetitive motion, which is frequently encountered in industrialized construction (e.g., manually feeding wood studs in wall framing machines, placing insulation on wall panels, and installing hardware on window frames) due to the standardization of products, intensifies muscular tension even if awkward body posture is not required and force level is low (Occupational Health and Safety Council of Ontario 2010). Indeed, forceful exertion, awkward body posture and motions repetitions are pointed out as the primary causes of WMSDs in industrialized construction (Li et al. 2019). WMSDs lead to higher absenteeism, injury rates, and early retirement, thus resulting in significant loss of productivity (Botti et al. 2017; Rajabalipour Cheshmehgaz et al. 2012).

In industrialized construction, due the centralization of processes in the production line, the extent of worker exposure to the risk of WMSDs is largely a function of workstation design and facility layout (Michalos et al. 2018). This centralization allows controlling workers exposure to risk of WMSDs by preventing ergonomic risks through design solutions at early design stage, which is considered as one of the most effective approaches to prevent occupational injuries (Golabchi et al. 2018b; Jia et al. 2011; Weinstein et al. 2005). Traditionally, ergonomic analyses of workplaces are conducted by observing workers in the production line. In this scenario, the production line is already in operation, meaning that any alterations to workstation design or facility layout will be costly and time-consuming (Peruzzini et al. 2019). To identify and minimize ergonomic risks in an effective and proactive manner, then, an assessment of these risks is required during the initial phases of workstation design. Conventionally, this assessment is conducted using physical prototypes—mock-ups. However, the use of mock-ups for this purpose is costly and laborious (Deviprasad and Kesavadas 2003; Seth et al. 2011). Indeed, physical prototyping methods require the commitment of major resources to identify shortcoming associated with design, evaluation, and fabrication processes as pointed out by Aziz (2018) and Choi and Chan (2004). Therefore, the use of other prototyping methods such as virtual prototyping is suggested as an alternative approach to quickly evaluate and test design features/parameters thus reducing physical iterations typically required during design development (Azizi et al. 2018; Garg and Kamat 2014).

Virtual reality (VR) is defined as a simulation that, from the generation of immersive virtual environments, users can experience and provide unique insights of real-world elements, projects, activities, etc. (Kim et al. 2013; Whyte 2007). According to Li et al. (2018), "VR attempts to replace user's perception of the surrounding world with a computer-generated artificial 3D environment". Moreover, by providing representational fidelity of the real-world, feeling of presence and immersion, and high level of engagement, VR allows users to manipulate, interact, and explore 3D environments in real time (Sampaio et al. 2010). In terms of industrial applications, VR facilitates virtual prototyping by allowing users to experiment and to assess prototypes in a realistic manner during early design development (Wolfartsberger 2019). Furthermore, the use of VR during early design phases allows for setups to be easily modified and also enables design reviews based on participant interactions with the project at a real scale, which traditionally would occur at a later stage using physical prototypes; in this way it aids in the decision-making process (Berg and Vance 2016; Davila Delgado et al. 2020; Pontonnier et al. 2013). Seth et al. (2011) state that the use of VR is ideal to simulate assembly activities since they require regular and intuitive manual interaction. Hence, VR appears as a supporting technology capable of overcoming the mentioned disadvantages of using physical mock-ups. This, in turn, enables the assessment of ergonomic risks even during the design phase of production lines.

VR applicability to the construction industry has been explored in several studies, with the areas of application ranging from virtual prototyping (Deviprasad and Kesavadas 2003; Li et al. 2012b), to training on construction equipment and maintenance tasks (Barkokebas et al. 2019; Li et al. 2012a; Rezazadeh et al. 2011), validation of simulation studies (Rekapalli and Martizes 2011), investigation of the built environment (Zhang et al. 2020), and ergonomic analysis (Dias Barkokebas et al. 2020; Hadikusumo and Rowlinson 2002). In terms of ergonomic analysis, researchers verified that VR allows proactive ergonomic investigation of workplaces in order to identify ergonomic risks (Azizi et al. 2018; Dias Barkokebas et al. 2020; Peruzzini et al. 2019). Nonetheless, VR potential for ergonomic risk assessment of manual handling industrialized construction tasks has yet to be better investigated since previous studies have focused on integrating software tools to virtual environments (Hadikusumo and Rowlinson 2002), testing and validating an experiment design (Dias Barkokebas et al. 2020), applying mixed prototyping (Peruzzini et al. 2019), and using virtual participants to carry out experiments (Azizi et al. 2018). Therefore, it is critical to explore the use of VR for ergonomic purposes in order to promote a proactive ergonomic risk assessment that identifies and mitigates ergonomic risks in the initial phases of workstation design. In this scenario, the need for physical mock-ups is eliminated through the simulation of real-world tasks in an immersive environment, thereby reducing the cost and time required to modify and implement an improved workstation design on the production line.

In this context, a gap in the literature is identified in regard to applying VR to evaluate workers' body movements in an industrialized construction environment, particularly with respect to rating ergonomic risk of manual handling tasks for the purpose of identifying and reducing workers exposure to ergonomic risks, thus minimizing the incidence of WMSDs. In order to fill this gap, the objective of the research presented in this paper is threefold: (1) investigate the human body movements involved in manual handling tasks in industrialized construction operations, (2) advance the use of VR for ergonomic risk rating analysis during initial phases of workstation design by proposing a VR-based ergonomic assessment methodology, and (3) verify the accuracy of the proposed methodology.

4.2. Background and Literature Review

To prevent WMSDs in industrialized construction it is essential to promote the design of safe workplaces, which entails acting on design characteristics that result in repetitive motions, awkward body postures, and forceful exertion (Li et al. 2015; Rajabalipour Cheshmehgaz et al. 2012; Inyang et al. 2012). Ergonomic risks can be assessed by analyzing two primary factors: (a) body posture, and (b) biomechanics. While the former evaluates ergonomic risks based on body joint angles, force loads, and interactions between the human body and the workplace (Golabchi et al. 2016), the latter focuses on musculoskeletal loads and stresses on joints (Armstrong et al. 1996). Rapid Entire Body Assessment (REBA) (Hignett and McAtamney 2000) and Rapid Upper Limb Assessment (RULA) (McAtamney and Corlett 1993) are examples of existing methods that focus on body posture analysis; while 3D Static Strength Prediction Program (3DSSPP) and

OpenSim are methods that focus on biomechanical analysis. Ergonomic assessment methods can also be categorized as either observation-based or computer-based. In observation-based methods, information on worker body posture is collected by means of subject observation, either directly on site or by viewing recorded video footage, and post-analysis estimation of joint angles (Roman-Liu 2014). These methods use predefined rules to calculate a quantitative risk score based on worker posture that in turn is associated with a qualitative risk rating. The REBA and RULA tools mentioned above, frequently used in existing research studies, are classified as observation-based techniques. For instance, to obtain a RULA score, information on the use of arm and upper body muscles, on force load, and on the positioning of legs as well as on the joint angles of the upper and lower arms, neck, trunk, and wrist is needed (McAtamney and Corlett 1993). REBA, meanwhile, focuses on the entire body, meaning that detailed information on joint angles of legs is required in addition to the inputs required by RULA (Hignett and McAtamney 2000). In computer-based methods, in contrast, reach assessment and prediction of biomechanical strength, metabolic rate, and time required to complete a task are used as the basis for ergonomic analysis using a computer software tool such as 3DSSPP (Feyen et al. 2000).

The physical demands of workstation design in industrialized construction have been investigated extensively in previous studies. Inyang and Al-Hussein (2011) proposed frameworks to conduct ergonomic risk assessment on a construction manufacturing assembly line. Li et al. (2017b) and Abaeian et al. (2016) assessed muscle activity during repetitive manual material handling operational tasks. Li et al. (2019a) proposed an improved physical demand analysis tailored to activities encountered in industrialized construction. In another study, Golabchi et al. (2018a) integrated ergonomic analysis in the evaluation and design of construction operations. To overcome the challenges encountered when attempting to collect precise information on body joint angles, Li et al. (2017a, 2019b) and Golabchi et al. (2015) proposed the application of 3D models that automatically identify and assess ergonomic risks in industrialized construction facilities. In addition, other studies (Bortolini et al. 2020; Ikuma et al. 2011; Ritter et al. 2019) have explored the application of ergonomics in the design of workplaces and factory layout to minimize ergonomic risks without compromising productivity.

The application of existing ergonomic assessment techniques, primarily REBA and RULA, integrated with VR to analyze risks in manufacturing tasks has been proposed by Peruzzini et al. (2019), Daria et al. (2018), Caputo et al. (2018), Vosniakos et al. (2017), Azizi et al. (2018), and Pontonnier et al. (2013). Although relatively few studies have investigated the application of VR to ergonomic analysis in a factory environment; those that are available do not focus on the industrialized construction industry. Moreover, these existing studies used mixed prototyping, which combines both virtual and real objects (e.g., participant holds a real angle grinder while approaching a virtual pipe) to conduct analysis (Peruzzini et al. 2019; Vosniakos et al. 2017); used an existing computer software tool such as DELMIA Ergonomics to calculate RULA scores (Azizi et al. 2018; Peruzzini et al. 2019); conducted experiments either in the factory to validate the design of a virtual workstation by filling in the European Assembly Work Sheet checklist (Caputo et al. 2018) or entirely in a virtual environment where both participants and tasks were virtual elements (Azizi et al. 2018); derived information on human body motion (i.e., estimation of joint angles) based on the frame-by-frame observation of a video recorded of a human character built in Unity 3D software (Vosniakos et al. 2017); or proposed a theoretical methodology the application and effectiveness of which were not demonstrated through a case study, such as in the case of Daria et al. (2018). In terms of ergonomic risk analysis, the aforementioned studies have determined risk ratings solely on the basis of motion data extracted from the virtual scenario (e.g., Vosniakos et al.

2017; Azizi et al. 2018), such that a meaningful comparison between real and virtual environments is not achieved; have focused on the comparison of joint angles acquired with motion capture (MOCAP) sensors (Caputo et al. 2018); have compared joint angles associated with a task performed in both real and virtual environments based on kinematics outputs, concluding that the virtual environment led to lower RULA scores (Pontonnier et al. 2013); and have compared RULA scores calculated using an existing software tool and the traditional observation method (Peruzzini et al. 2019). Hence, these studies are limited to the (a) calculation of RULA scores based on existing commercial software that either simulates human motions or generates videos used for ergonomic analysis, (b) use of mixed prototyping, and (c) use of virtual participants, or (d) application in a case study is still absent, or (e) a comparison between ergonomic risk ratings derived from different environments is not conducted. In addition, according to Pontonnier et al. (2013), performing ergonomic studies of industrial assembly tasks using VR is a challenge due to the discrepancy observed in the RULA scores obtained in real versus virtual environments, which indicates opportunities for future research.

The aim of this study is to address the aforementioned limitations as well as bridge a gap in the literature by proposing and validating a VR-based ergonomic risk assessment approach through a case study, based on frame-by-frame observation of real participants, that can aid in evaluating workstation design ergonomics. By doing so, this study contributes to the body of knowledge in that it provides an updated comparison of ergonomic risk assessment based on the observation of tasks conducted in both real and VR environments, thereby verifying the effectiveness of the use of VR technologies to conduct ergonomic risk rating analysis of manual handling tasks in the industrialized construction sector and reducing the mentioned discrepancy between RULA scores obtained in real and virtual environments.

4.3. Methods

4.3.1. Overview

This study is built upon the hypothesis that applying VR to conduct human body motion analysis can assist in identifying ergonomic risk ratings of manual handling operational tasks in industrialized construction in a safe and controlled environment, providing ergonomic feedback during workplace design, and thereby decreasing both cost, by reducing the need for physical mock-ups, and workers long-term exposure to ergonomic risks that can lead to WMSDs. To verify this hypothesis, a VR application was designed, tested, and applied in order to simulate the maintenance task of a wood framing machine. As illustrated in Figure 4.1, six procedures were followed to achieve the objectives of this study: (1) design VR application to simulate a task performed in an industrialized construction facility; (2) design questionnaire to obtain participant feedback on the VR application; (3) conduct experiments in two environments, virtual and real, to acquire information on human body motions; (4) analyze data collected in the questionnaire and capture body joint angles from the videos recorded during the experiments to use for ergonomic analysis; (5) assess ergonomic risks, which consists of using the body joint angles captured in (4) as inputs to two existing ergonomic risk assessment tools, RULA and REBA (both methods are often applied in research studies due to their capability of providing accurate results based on simple input information (Li 2017, Manghisi et al. 2017, Azizi et al. 2018)); and (6) compare risk assessments obtained with VR and real mock-ups to verify the suitability of VR to conduct ergonomic risk rating analysis. It should be noted, this study is an extension of the study developed by Dias Barkokebas et al. (2020), which focused on the experiment design.

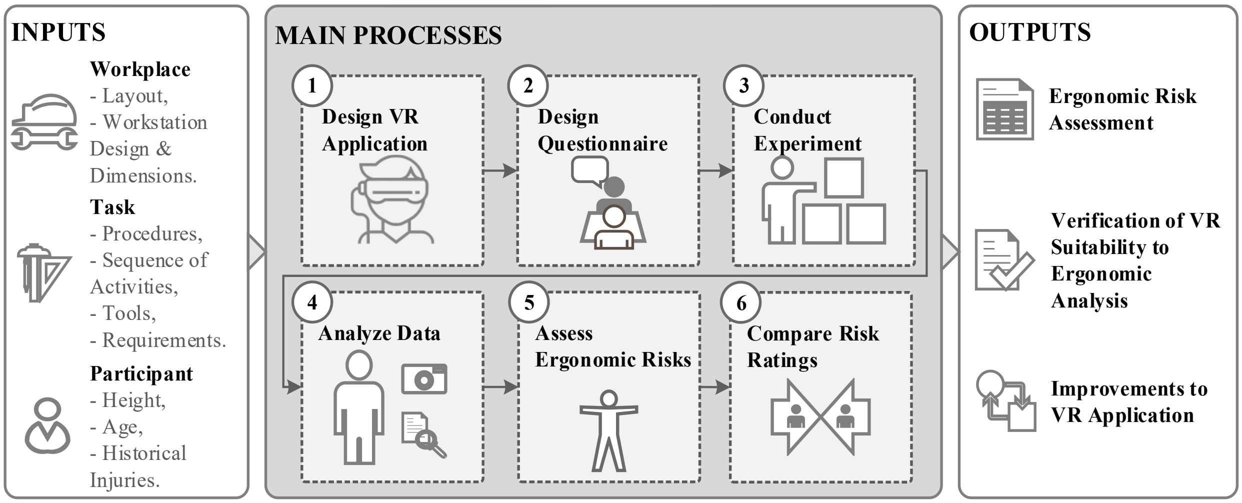


Figure 4.1: Overview of proposed methodology.

4.3.2. Design Virtual Reality Application

A VR simulation consists of 3D elements integrated with user interactions developed using game engine software. The approach followed to design the VR application used in this study consisted of seven phases as illustrated in Figure 4.2. In phase one, information on the workstation was acquired based not only on detailed drawings, 2D and 3D, but also on site visits to verify if the mock-up of the workstation has been built according to the design specifications as well as to capture workers interaction with the workstation being investigated. When the workstation being investigated is in its initial design phase and therefore its physical mock-up has not been assembled, the information available from the detailed drawings is used to design the VR application and the interactions of workers with the workstation are assumed based on the task being evaluated and on the interactions performed on similar workstations. From the drawings, 3D elements and shapes were imported to 3ds Max in Phase 2. Interactions and visualization features were added in phase 3 using a game engine software, which also dictates the sequence of activities and behaviour of objects. In this study, Unreal Engine 4.22 was selected as the game engine software due to its capabilities of developing realistic virtual environments and robust interactions using Blueprint Visual Scripting, which is a system that eliminates the need for traditional programming languages by using a node-based interface to generate gameplay scripts (Paravizo and Braatz 2019). The interactions added in the game script are essential to the development of an accurate VR application for ergonomic analysis. The data related to these interactions is based on the analysis of recorded videos and on notes made during site visits. To account for the interactions existing in the real-world, the developed VR application encompassed three types of elements: (a) movable elements, such as pieces of equipment that required to be relocated during the experiment; (b) stationary elements (e.g., scenario elements), with static properties; and (c) non-interactive elements, such as the tag showing progression status (Figure 4.3.a). A highlighting feature was applied to indicate the tool and piece of equipment that the participant should work on (Figure 4.3.b and Figure 4.3.c), task progression status could be monitored throughout the experiment (Figure 4.3.a), and virtual hands were implemented in the gameplay script and 3D modelling (Figure 4.3) to allow a better visualization of the commands triggered by the hand controllers as well as to increase participant's understanding of his/her hands and arms movements. To ensure that the VR application and the physical mock-up are sufficiently similar (e.g., dimensions and aesthetics), the dimensions used to build both were obtained from the same design documents and, once the physical mock-up was assembled, most relevant dimensions and interactions (i.e., operational aspects) were verified and cross-checked with the developed VR application in phase 4. In phase 5, adjustments were made in the VR application to better represent the task being investigated. Once the designed VR application was considered a suitable representation of the physical mock-up, a pilot test, which will later be described in detail in the paper, was run in step 6 and its results were analyzed in step 7. The design of the VR application was concluded only when dimensions, aesthetics, interactions, and preliminary ergonomic results were compatible to those of the physical mock-up. The approach followed herein can be replicated to the development of other VR application, including applications for other research domains.

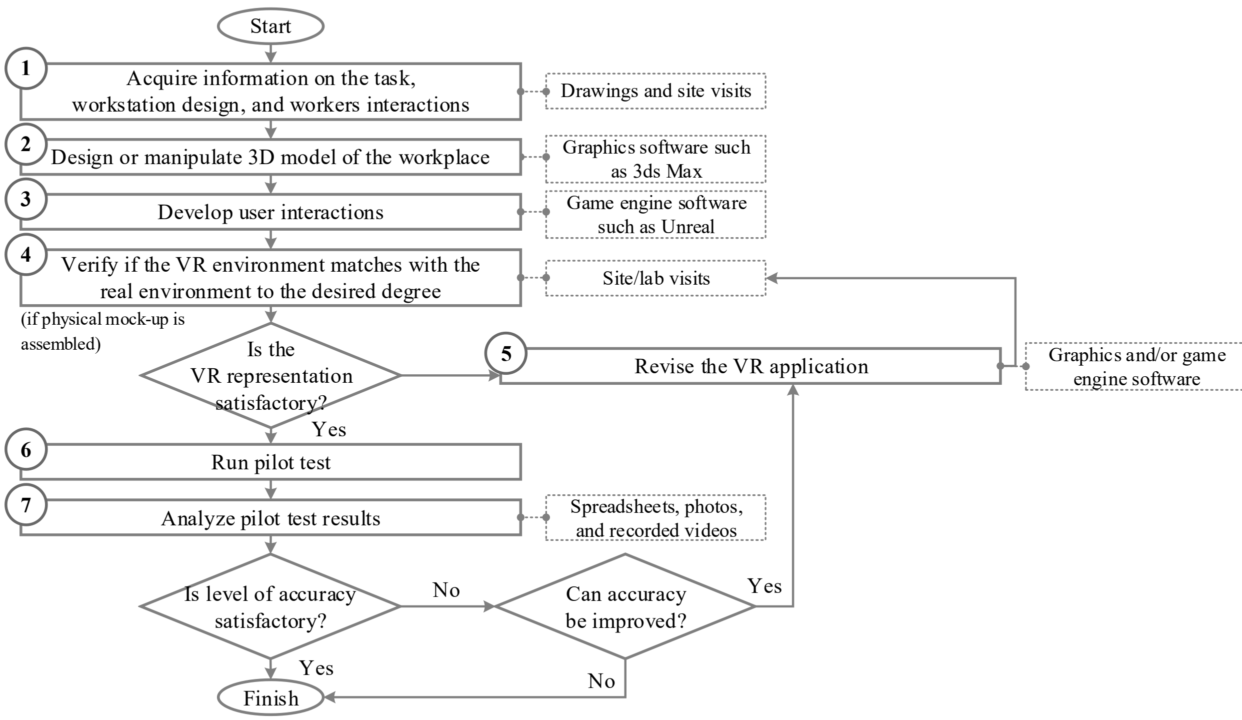
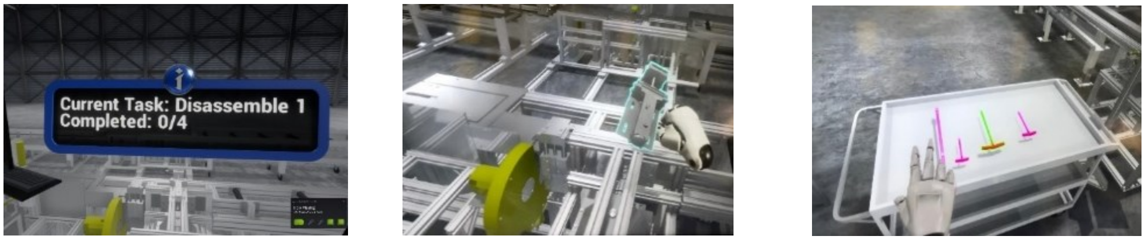


Figure 4.2: Overview of proposed methodology to design VR applications.



a. Task progression status.

b. Highlighting feature on equipment.

c. Highlighting feature on tools.

Figure 4.3: Examples of features included in the designed VR application.

The physical space where the VR equipment was installed and where the VR experiments were carried out is a 3.65 m × 6.00 m VR lab located in a research facility. This VR lab accommodated an HTC VIVE system composed of two hand controllers, one headset, and two base stations as well as one 75″ TV, two tables, a computer to run the VR experiment, and video recording equipment. The boundaries of the VR system defined a play area of approximately 3.40 m × 2.70 m in which participants could move freely, safely, and with minimal interference from the real world.

4.3.3. Design Questionnaire

The questionnaire was designed to collect information on participants and their perception of the developed VR application with the following objectives: (a) verify if the approach pursued to develop the VR application (Figure 4.2) resulted in a satisfactory representation of the real environment from the perspective of participants with respect to virtual aesthetics, dimensions, and user interactions; (b) assess if the designed VR application has good user experience; (c) contribute to determine whether the VR application can reduce the need for physical mock-ups, thus decreasing resources commitments such as material, time, and labour; and (d) identify areas of potential improvement for the designed VR and future VR applications in the same research domain and in others. The questionnaire was divided into four main portions: (1) background of participants, (2) usability of VR, (3) task simulation, and (4) additional feedback. In the first portion, participants were asked to provide information such as gender, age, education level, previous injuries that may impact on their performance in the VR application, whether or not they wear corrective glasses, and whether or not they have had prior experience with VR. The second and third portions focused on capturing participants' feedback on their interaction with the virtual application and its level of accuracy, and this was acquired with five-point Likert Scale questions (i.e., strongly disagree = 1, strongly agree = 5). The selection of questions was based on existing studies conducted in the same research area (Paravizo and Braatz 2019; Peruzzini et al. 2019; Wolfartsberger 2019) as well as on considerations specific to the task being investigated. In the fourth portion, participants were given the opportunity to provide additional feedback about their experience participating in this study. A link to the questionnaire, which was designed and administered using Google Forms, was sent to participants by email once they have completed their participation in the experiment.

4.3.4. Conduct Experiment

4.3.4.1. Study Scenario and Experimental Setup

Several studies state that the most critical challenge associated with the use of simulation techniques, such as VR and 3D animations, is to verify to what extent the simulation provides a realistic representation of a real-world situation. To overcome this challenge, it is recommended to use a simple task from which results of both real and simulated environments can be obtained and compared (Maline and Pretto 1994; Paravizo and Braatz 2019). For this reason, a task that could be replicated in both real and virtual environments was chosen in this study to validate the proposed method. The task consisted of a sequence of six subtasks involved in the disassembly of the drilling module of a semi-automated wall framing machine. The virtual scenario represented an industrialized construction facility with a wood framing machine, a cart with tools available for the participant, and a table where the pieces of equipment were placed. To disassemble the component, the participant used both of their hands and various tools as described in Figure 4.4. Although the task required participants to lift machinery pieces, these pieces weighed less than 2 kg each and were carried only intermittently. As such, their weight did not impact on RULA and REBA scores (McAtamney and Corlett 1993; Hignett and McAtamney 2000), and thus was disregarded in the analysis conducted in this study.

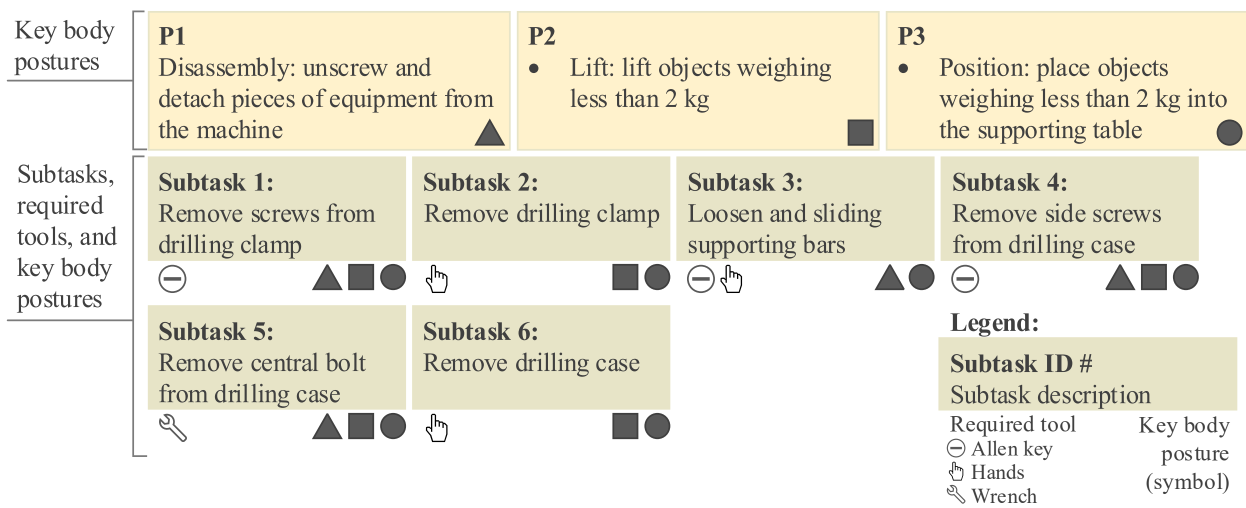


Figure 4.4: Description of subtasks, required interactions, and key body postures.

In a within-subject designed experiment all participants are exposed to the conditions being tested, therefore, participants' behaviours across different environments can be observed. In addition, small differences between participants' performance, regardless of the sample size of participants, are also detected (Charness et al. 2012; Fellows and Liu 2008). For these reasons, this study carried out a within-subject designed experiment which was divided into two phases: (1) VR application, and (2) physical mock-up. Both phases were carried out in the same research facility. In Phase 1, participants were given instructions on how to operate in the VR application prior to initiating the experiment. Once Phase 1 was concluded and after a rest period that varied between 10 and 20 minutes, the same task was performed in the real world using a physical mock-up of the machine (Phase 2). Since the analysis performed herein did not involve intellectual skills (i.e., learning and adaptational skills); the length of the investigated task was short thus reducing the risk of fatigue, and adaption or learning effects due to long-term exposure to the conditions being tested; and considering that rest periods between experiments were provided, the impact of the VR section on the physical mock-up section was minimized. In cases that intellectual skills are relevant to the analysis, either the sequence of environments (i.e., VR and real) should be randomly attributed to participants to avoid effects on participants' performance or participants should receive sufficient time to practice in both environments to guarantee that learning plateaus are achieved in each environment (Wilson and Corlett 2005).

In both phases, participants were being video-recorded for post-experiment ergonomic analysis purposes. Although MOCAP systems can aid in ergonomic analysis, their implementation is still costly; alternatively, video cameras are recommended as a cost-effective approach to acquire posture-based information, especially due to their capability of obtaining relevant and accurate data without disrupting the participant (Li and Buckle 1999). Furthermore, ergonomic assessments based on manual observation have been extensively applied in practice due to its legitimacy, easiness, and accessibility (Golabchi et al. 2016).

4.3.4.2. Pilot test

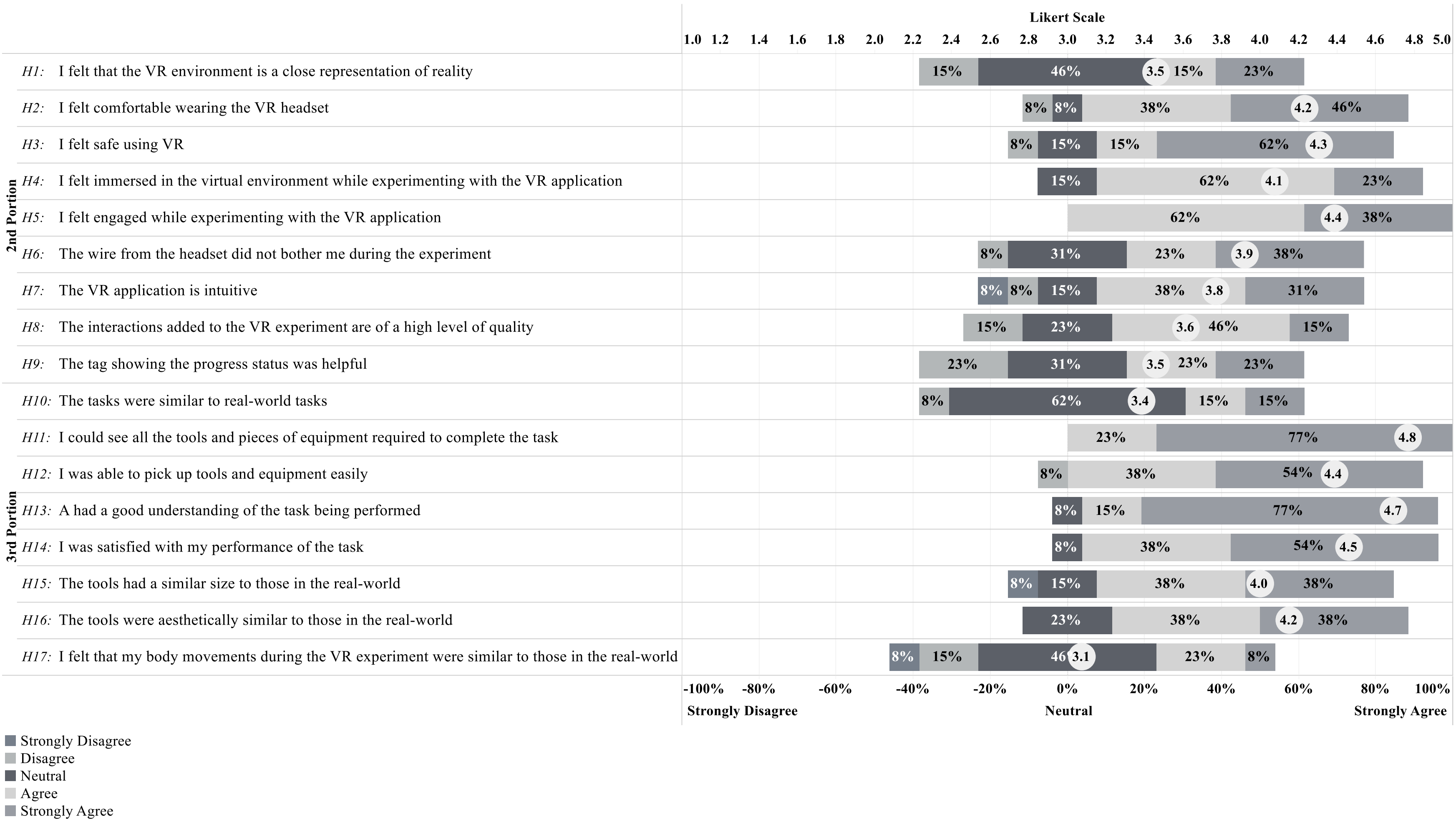
A pilot study of the VR experiment has been conducted with four participants (Dias Barkokebas et al. 2020). Based on the feedback received, minor improvements have been made to the application to enhance its applicability to ergonomic analysis. (For further information on the pilot study of the VR application, the reader may refer to Dias Barkokebas et al. (2020).)

4.3.4.3. Participants

An invitation to voluntarily participate in this study was distributed by email to engineering students of the University of Alberta. The primary objective of the experiment was to obtain ergonomic risk ratings associated to the completion of a task in both real and virtual environments for comparison purposes to validate the methodology proposed in this study; as such, the fact that participants were not construction workers is deemed acceptable. Before recruiting participants, the authors have received approval by the pertinent ethics board, hence, this study's adherence to ethical guidelines related to the observation of humans is ensured.

4.3.4.4. Analyze Data

This study analyzed two distinct types of information: (1) questionnaire responses and (2) body joint angles for ergonomic risk assessment. As mentioned in the Design Questionnaire subsection above, the questionnaire collected participant feedback in response to several hypothesis statements, H_x. In order to analyze the responses obtained for each hypothesis, the average H_x score, $\bar{x}$, and the distribution of responses by Likert scale value were determined. For conciseness, both hypotheses and questionnaire results are shown in Figure 4.5.



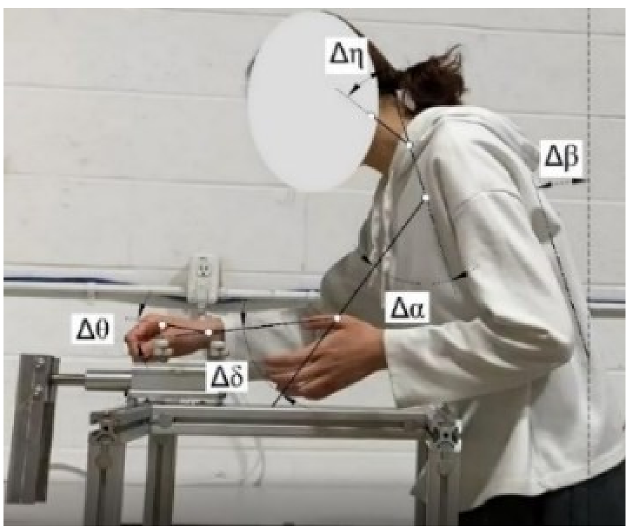
Note: average score indicated in light-grey circles.

Figure 4.5: Questionnaire results.

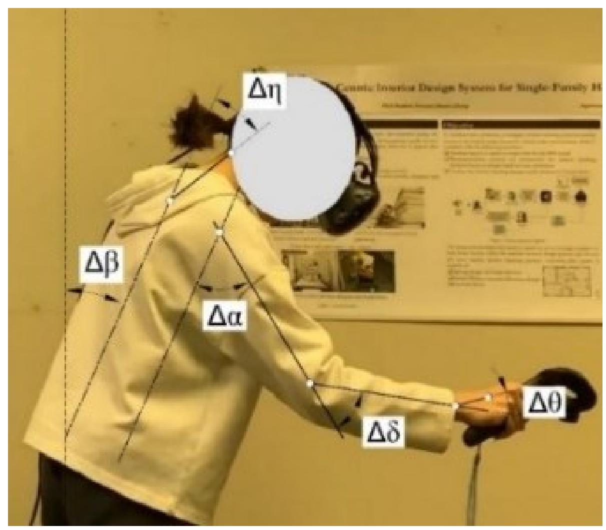
With respect to ergonomic risk assessment, the body joint angles needed for RULA and REBA analyses were obtained in three steps: (a) preliminary analysis of videos recorded during the experiment to determine key body postures to be analyzed in each subtask, (b) frame-by-frame analysis of videos recorded during the experiment to select frames containing the defined key body postures from which relevant angles were to be estimated, and (c) estimation of participant body joint angles from the selected video frames. Based on the determined key body postures, each subtask was divided into 2 or 3 postures, as detailed in Figure 4.4, meaning that 15 video frames were selected for each environment and participant. As shown in Figure 4.4, Subtasks 2 and 6 did not have P1, and Subtask 3 did not have P3 due to the nature of these subtasks; for instance, the screws that attached the drilling clamp to the supporting bars were removed (P1) in Subtask 1, for this reason, Subtask 2 focused on lifting the drilling clamp (P2) and placing it on the supporting table (P3).

The selection of the 15 video frames per participant and environment was done in such a manner that the worst-case scenario for RULA and REBA scores was assumed—i.e., from the preliminary observation of the recorded videos, the portion of the subtask with a key body posture and with the highest ergonomic risk for most participants was identified, and the video frame corresponding to this portion was thus selected for further analysis. To ensure that the key body posture analyzed (i.e., selected video frame) was equivalent in both environments as well as among all participants (meaning that they were all performing a similar motion), the seven subtasks were further divided into more specific task elements, in addition to the breakdown per body posture, such as unscrewing the top screw from the left side of the drilling clamp, as exemplified in Figure 4.6. Video frames were selected from the same sub portion of the subtask encompassing pertaining key body posture for all participants. Similar to in the studies of van't Hullenaar et al. (2017), Ray and

Teizer (2012), and Golabchi et al. (2018a), body joint angles were derived from vectors superimposed on images extracted from the selected video frames (Figure 4.6). The mentioned vectors were drawn by the same individual using existing software and, once they were drawn, the angles between the vectors (i.e., body members) were automatically and objectively calculated using an annotation command available in the software. As illustrated in Fig. 6, the same angles ($\Delta\alpha$ = upper arm, $\Delta\delta$ = lower arm, $\Delta\theta$ = wrist, $\Delta\eta$ = neck, $\Delta\beta$ = trunk, and $\Delta\vartheta$ = leg) were collected in both real and virtual environments. These angles were selected as they were required for the RULA and REBA assessments as detailed in the next section.



a. Physical mock-up.



b. VR.

Figure 4.6: Body angles required for ergonomic risk assessment of upper body members.

4.3.4.5. Assess Ergonomic Risks

In this study, both RULA and REBA assessments are chosen as the methods to evaluate ergonomic risks for the following reasons: their applicability for assessing assembly processes has been verified in previous studies (Golabchi et al. 2015; Vosniakos et al. 2017) and, as observational methods, their implementation is simple, practical, and affordable (David 2005). As detailed in

Table 4.1, ergonomic risks in both RULA and REBA assessments are defined according to the angles formed between body members (McAtamney and Corlett 1993; Hignett and McAtamney 2000). In addition, adjustment factors are applied to upper and lower arms, wrist, neck, and trunk to account for conditions such as bending, twisting, and abducting. The assessment of muscle use is done separately for arms and upper body taking into consideration the time a posture is held and its frequency per minute. In terms of force load, two aspects are accounted for: load and type of action (e.g., intermittent, repeated, and static). Therefore, repetitive motions are accounted for in both methods, which is particularly important when analyzing operational tasks of industrialized construction. Once information on these three categories (i.e., body joint angles, muscle use, and force load) is obtained, a score is calculated. The interpretation of risks levels according to the calculated score is as follows: for RULA, 1–2 = negligible, 3–4 = low, 5–6 = medium, and 6+ = very high; while for REBA, 1 = negligible, 2–3 = low, 4–7 = medium, 8–10 = high, and 11–15 = very high (McAtamney and Corlett 1993; Hignett and McAtamney 2000). In both assessment methods, the necessity of changes/actions to minimize ergonomic risks is determined according to the risk level, where negligible = no action is required, low = changes may be necessary, medium = further investigation is required and changes are necessary, high = changes should be done soon, very high = changes should be made. In this study, both RULA and REBA risk assessments were conducted assuming the participant was using their dominant hand. The body joint angles derived as described in the previous section were used as input in RULA and REBA assessments.

Table 4.1. RULA and REBA ranges of joint angles and corresponding risks.

Risk	Upper arm (RULA & REBA)	Lower arm (RULA & REBA)	Wrist (RULA)	Wrist (REBA)	Neck (RULA)	Neck (REBA)	Trunk (RULA & REBA)	Legs (REBA only)
Low	$-20° \leq \Delta\alpha \leq 20°$	$50° \leq \Delta\delta \leq 100°$	$\Delta\theta = 0°$	$-15° \leq \Delta\alpha \leq 15°$	$0° \leq \Delta\eta \leq 10°$	$0° \leq \Delta\eta \leq 20°$	$\Delta\beta = 0°$	Legs/feet supported
	$-20° \geq \Delta\alpha$	$0° \leq \Delta\delta \leq 50°$	$-15° \leq \Delta\alpha \leq 15°$	$-15° \geq \Delta\alpha$ or $15° \geq \Delta\alpha$	$10° \leq \Delta\eta \leq 20°$	$\Delta\eta \geq 20°$ or $\Delta\eta < 0°$	$0° \leq \Delta\beta \leq 20°$ [$\Delta\beta \leq 0°$ (REBA only]	Legs/feet not supported
	$46° \leq \Delta\alpha \leq 20°$	$\Delta\delta \geq 100°$	$-15° \geq \Delta\alpha$ or $15° \geq \Delta\alpha$		$\Delta\eta \geq 20°$ or		$20° \leq \Delta\beta \leq 60°$	$30° \leq \Delta\vartheta \leq 60°$
	$90° \leq \Delta\alpha \leq 45°$				$\Delta\eta < 0°$		$\Delta\beta \geq 60°$	$\Delta\vartheta \geq 60°$ (REBA only)
High	$90° \geq \Delta\alpha$							

Source: Data from McAtamney and Corlett 1993; Hignett and McAtamney 2000.

4.3.5. Compare Risk Ratings

To verify the accuracy of the proposed VR-based ergonomic risk assessment methodology, both RULA and REBA risk scores of participants performing the task in real and virtual environments were compared using Equations (1)-(5), where i stands for subtask ID, p for posture ID, j for participant ID, n for total number of participants, and m for total number of key body posture analyzed per participant.

$$\overline{Difference}\ (\bar{d}_{i,p}) = \sum_{i=1}^{n} (RR_{i,p} - RV_{i,p}) \tag{1}$$

$$\overline{Error}\ (\bar{e}_{i,p}) = \frac{\bar{d}_{i,p}}{n} \times 100\% \tag{2}$$

$$Compatible\ scores\ per\ subtask\ and\ key\ body\ posture\ (\bar{c}_i) = \sum_{i=1}^{n} \frac{C_i}{n} \times 100\% \tag{3}$$

$$Compatible\ scores\ per\ participant\ and\ key\ body\ posture\ (\bar{c}_j) = \sum_{i=1}^{n} \frac{C_i}{m} \times 100\% \tag{4}$$

where

if:

$RR_{i,p,j} - RV_{i,p,j} = 0, \Rightarrow C_i = 1$

(5)

Otherwise,

$\Rightarrow C_i = 0$

$RR_{i,p}$ or $RR_{i,p,j}$: RULA or REBA score obtained in the real-world per key body posture of subtask or per key body posture of subtask and participant, respectively;

$RV_{i,p}$ and $RV_{i,p,j}$: RULA or REBA score obtained in the VR per key body posture of subtask or per key body posture of subtask and participant, respectively.

4.4. Results and Discussion

4.4.1. Questionnaire Results

Altogether, 13 participants took part in the experiment and filled out the online questionnaire. As shown in Table 4.2, most participants were less than 30 years old, had used VR technologies before, and wear corrective glasses. Although the sample size is reduced, it complies with the recommendations of Azizi et al. (2018) and Barnes (1963) which state that a minimum of 10 people is required for studies focusing on this type of experiment.

Table 4.2. Characteristics of participants.

Characteristics of participants	Responses
Gender	
Male	8 (62%)
Female	5 (38%)
Age (years)	$\bar{x} = 27$ | $\sigma = 2$
Height (cm)	$\bar{x} = 176$ | $\sigma = 9$
Wear corrective glasses	Yes = 9 (69%) | No = 4 (31%)
Education level	

Graduate (Master or PhD – pursuing or completed)	12 (92%)
Bachelor (pursuing or completed)	01 (8%)
Have previous musculoskeletal injuries	03 (23%)
Have experienced VR applications before	11 (85%)

In terms of the usability of the developed VR application (i.e., the second portion of questionnaire), most participants reported that they felt safe, comfortable, engaged, and immersed in the VR application (Figure 4.5). Approximately 85% of participants reported feeling comfortable wearing the VR headset (H_2); among those, approximately 70% wear corrective glasses. We can thus conclude that wearing corrective glasses does not have a significant impact on participant comfort while using the developed VR application. To provide a closer representation of reality (H_1), the VR application still needs improvements according to participant feedback. Regarding the task under investigation (i.e., the third portion of the questionnaire), most participants strongly agreed that the VR application provided a good understanding of the task being performed (H_{13}) and that all tools and pieces of equipment were clearly visualized (H_{11}), which indicate that the designed VR provides a suitable representation of the real environment and also has good user experience. Although participants reported being satisfied with their performance of the task (H_{14}) and agreed that the tools had similar size and aesthetics to those encountered in the real-world (H_{15} and H_{16}), most participants felt that the virtual subtasks were not similar to those in the real-world (H_{10}), and thus they reported feeling an incongruity between their body movements in real versus virtual environments (H_{17}). The results obtained with respect to the hypotheses mentioned above are detailed in Figure 4.5.

Based on the feedback received and the analysis of recorded videos, the VR application will be modified to provide a more realistic representation of subtasks. This entails improving hand motions in the VR experiment, and addressing some challenges identified with respect to the physical mock-up, such as those to do with loosening the support bars (i.e., participants needed to hold the Allen key at a certain angle to complete this subtask) and removing the screws from the drilling clamp (i.e., once the participant removed two of the four screws, the clamp became imbalanced, requiring the participant to hold the clamp with one hand while loosening the remaining screws with the other hand). In addition, the tag showing the progress status (Figure 4.3.a) will be made an optional feature (rather than a standard feature), given the participant neutrality towards H_9. Besides assisting with identifying improvement areas for the VR application developed in the present study, this participant feedback is also applicable to the design of VR applications in other research areas. Furthermore, participants' feedback revealed that the approach pursued to develop the VR application (Figure 4.2) resulted in a satisfactory virtual environment in which participants had a good experience.

4.4.2. Ergonomic Risk Assessment

Altogether 390 video frames were analyzed, 195 video frames per environment, for both RULA and REBA risk assessments (i.e., 15 video frames of key body postures, covering the 6 subtasks, per the 13 participants). Samples of the chosen three key body postures are shown in Figure 4.7. As detailed in Table 4.3, the average ($\bar{x}$) RULA and REBA scores of all key body postures analyzed per subtask in both environments was either 3 or 4; a finding which suggests a low risk level based on RULA scores and either a low or medium risk level according to REBA scores. With respect to RULA, the P2 of Subtask 1 and P1 of Subtask 4 were the only postures for which the $\bar{x}$RULA score was not equivalent in both environments; however, $\bar{x}RR_{1,P2}$ and $\bar{x}RV_{1,P2}$, and

$\bar{x}RR_{4,P1}$ and $\bar{x}RV_{4,P1}$ were within the same risk rating, and this ensures correct interpretation of the RULA score. On the other hand, in postures in which $\bar{x}$REBA score was not equivalent in both environments, the interpretation of REBA score was affected, as $\bar{x}$REBA varied from a low (REBA = 3) to a medium (REBA = 4) risk level as observed in the P1 of Subtasks 1, 4, and 5. This finding suggests that using VR to calculate REBA scores of assembling postures may result in a higher ergonomic risk rating since only posture P1 showed discrepancy in terms of average risk score. Figure 4.8 and Figure 4.9 depict the distribution of RULA and REBA scores, respectively, per key body postures, subtasks, and environment. As observed in Figure 4.8 and Figure 4.9, participants faced ergonomic risks rated as "medium" level (i.e., RULA = 5 and 6, REBA = 4, 5, and 6) while performing the subtasks, which revealed that improvements should be made to minimize ergonomic risks. The RULA scores of 5 were a result of (a) high neck ($\Delta\eta \geq 30°$) and trunk ($20° \geq \Delta\beta \leq 60°$) joint angles combined with neck or trunk either twisted or side bending, (b) high neck joint angle ($\Delta\eta \geq 30°$) combined with neck and trunk side bending, or (c) high neck joint angle ($\Delta\eta \geq 30°$) combined with twisted neck and rotation of arm to the side of the body. The REBA scores of 5 were due to: (a) high neck ($\Delta\eta \geq 20°$), trunk ($20° \geq \Delta\beta \leq 60°$), and upper arm ($\Delta\alpha \geq 45°$) joint angles, (b) high upper arm ($\Delta\alpha \geq 45°$) and wrist ($\Delta\theta \geq 15°$) joint angles, (c) high trunk ($20° \geq \Delta\beta \leq 60°$) and upper arm ($\Delta\alpha \geq 45°$) joint angles combined with neck twisted. The RULA scores of 6 were a result of high neck ($\Delta\eta \geq 30°$) and trunk ($20° \geq \Delta\beta \leq 60°$) joint angles combined with neck twisted and trunk side bending, which was only observed in the P3 of Subtask 1. The REBA scores of 6, encountered in the P1 of Subtask 1, and in the P3 of Subtask 1 and 5, were a result of (a) high neck ($\Delta\eta \geq 20°$), trunk ($20° \geq \Delta\beta \leq 60°$), and either upper arm ($\Delta\alpha \geq 45°$) or lower arm ($\Delta\delta \leq 50°$) joint angles combined with neck twisted or trunk side bending. These results were in line with the fact that several participants reported, in the fourth portion of the questionnaire, feeling lower-back discomfort while performing the task. For these reasons, an increase in the height of the semi-automated framing machine under study was proposed to attenuate motions of the mentioned body parts.

a. P1 of Subtask 3. b. P2 of Subtask 6. c. P3 of Subtask 4.

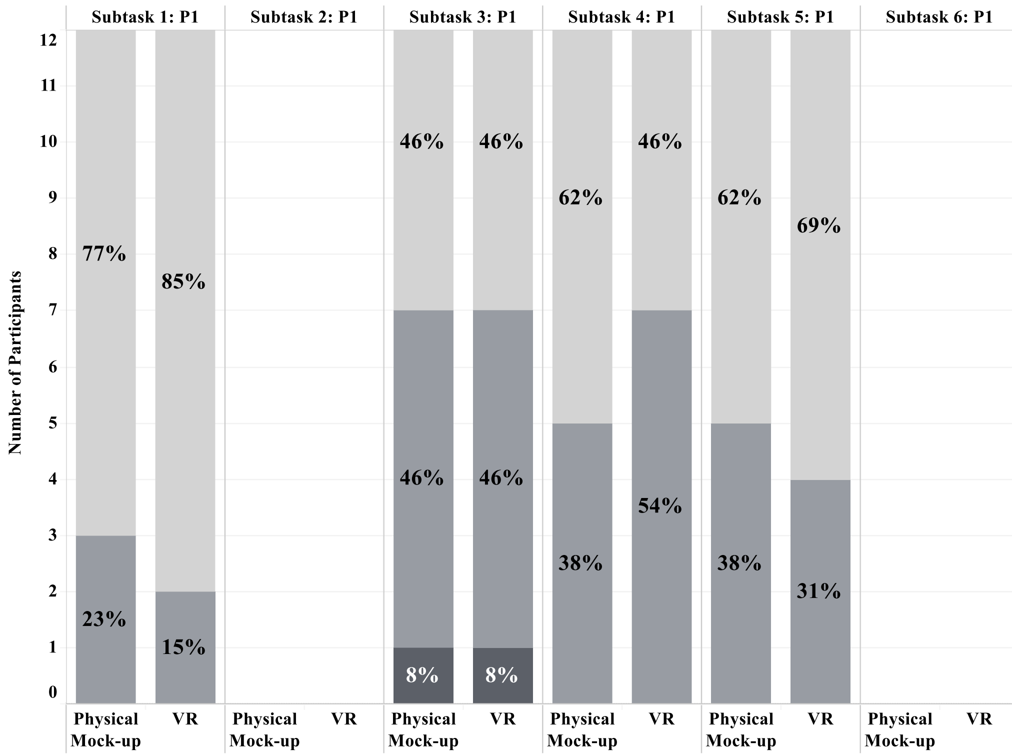
Figure 4.7: Example of key body postures analyzed per subtasks.

Table 4.3. Comparison of RULA and REBA scores per subtask, key body posture, and environment.

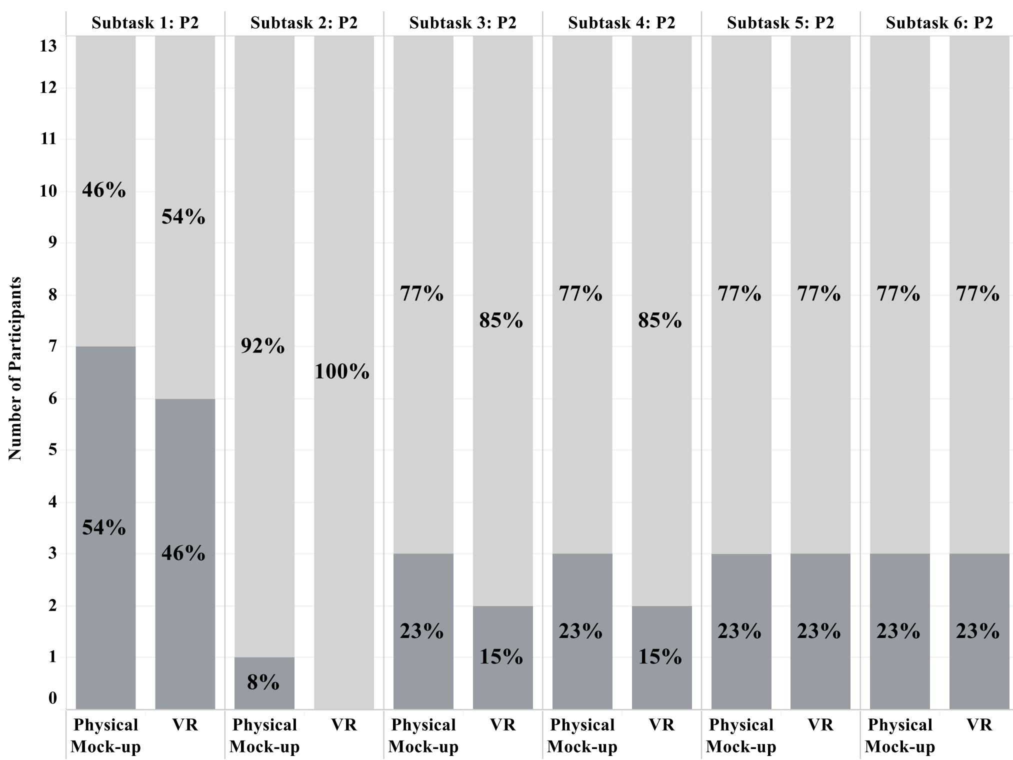
Subtask ID	Key body posture	Environment	RULA						REBA					
			$\bar{x}$[a]	σ	Risk level	$\bar{d}$	$\bar{e}$ [%]	$\bar{c}_i$ [%]	$\bar{x}$[a]	σ	Risk level	$\bar{d}$	$\bar{e}$ [%]	$\bar{c}_i$ [%]
Subtask 1	P1	VR	3	0.4	L	1	8	92.3	4	0.6	M	0	0	84.6
		Physical mock-up	3	0.4	L				4	0.6	M			
	P2	VR	3	0.5	L	1	8	76.9	3	0.7	L	0	0	76.9
		Physical mock-up	4	0.5	L				3	0.7	L			
	P3	VR	4	0.6	L	2	15	92.3	4	0.8	M	0	0	76.9
		Physical mock-up	4	0.6	L				4	1.0	M			
Subtask 2	P2	VR	3	0.0	L	1	8	92.3	3	0.5	L	1	8	92.3
		Physical mock-up	3	0.3	L				3	0.6	L			
	P3	VR	4	0.6	L	0	0	84.6	4	0.7	M	2	15	69.2
		Physical mock-up	4	0.4	L				4	0.8	M			
Subtask 3	P1	VR	4	0.7	L	1	8	92.3	4	0.7	M	2	15	76.9
		Physical mock-up	4	0.7	L				3	0.7	L			
	P2	VR	3	0.4	L	0	0	100	3	0.7	L	1	8	92.3
		Physical mock-up	3	0.4	L				3	0.6	L			
Subtask 4	P1	VR	4	0.5	L	2	15	84.6	4	0.8	M	3	23	84.6
		Physical mock-up	3	0.5	L				3	0.5	L			

	P2	VR	3	0.4	L	1	8	92.3	3	0.8	L	1	8	76.9
		Physical mock-up	3	0.4	L				3	0.7	L			
	P3	VR	4	0.5	L	3	23	76.9	4	0.6	M	1	8	76.9
		Physical mock-up	4	0.6	L				4	0.7	M			
Subtask 5	P1	VR	3	0.5	L	1	8	92.3	3	0.8	L	1	8	76.9
		Physical mock-up	3	0.5	L				4	0.8	M			
	P2	VR	3	0.4	L	1	8	92.3	3	0.6	L	1	8	92.3
		Physical mock-up	3	0.4	L				3	0.7	L			
	P3	VR	4	0.7	L	4	31	69.2	4	0.8	M	1	8	92.3
		Physical mock-up	4	0.6	L				4	0.7	M			
Subtask 6	P2	VR	3	0.4	L	0	0	100	3	0.7	L	5	38	69.2
		Physical mock-up	3	0.4	L				3	0.7	L			
	P3	VR	4	0.6	L	1	8	61.5	3	0.8	L	0	0	69.2
		Physical mock-up	4	0.5	L				3	0.8	L			

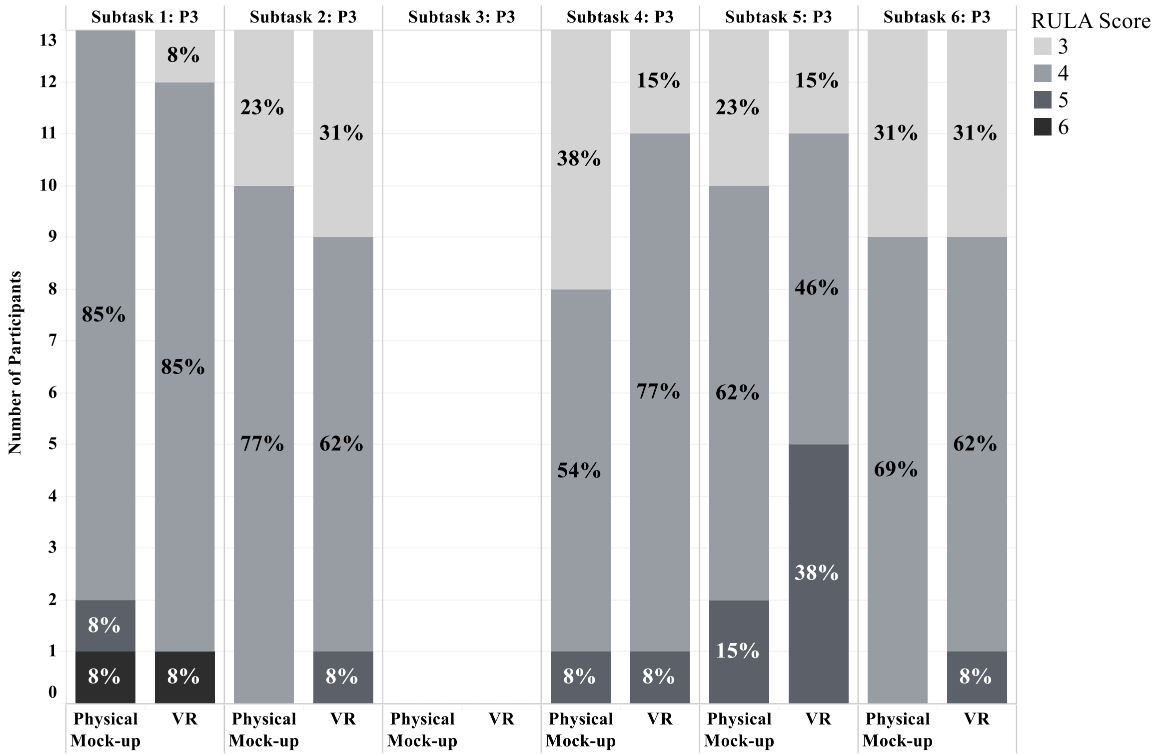
[a]Average RULA score is rounded to the closest integer. Note: “L”: Low; M: Medium.



a. Key body posture P1.

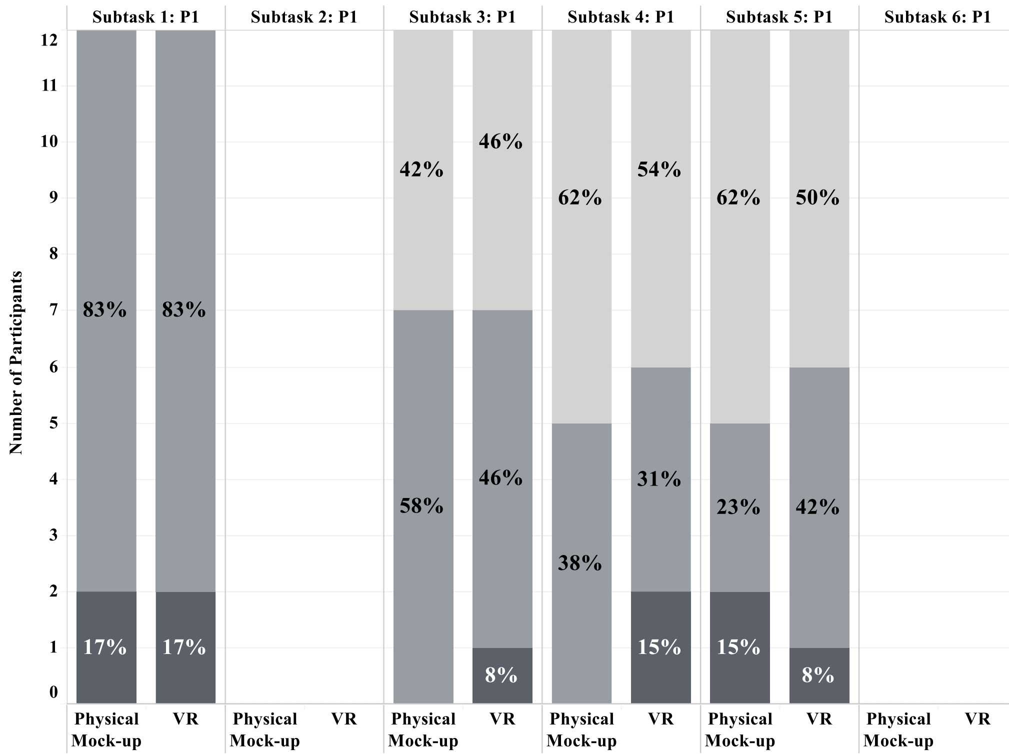


b. Key body posture P2.

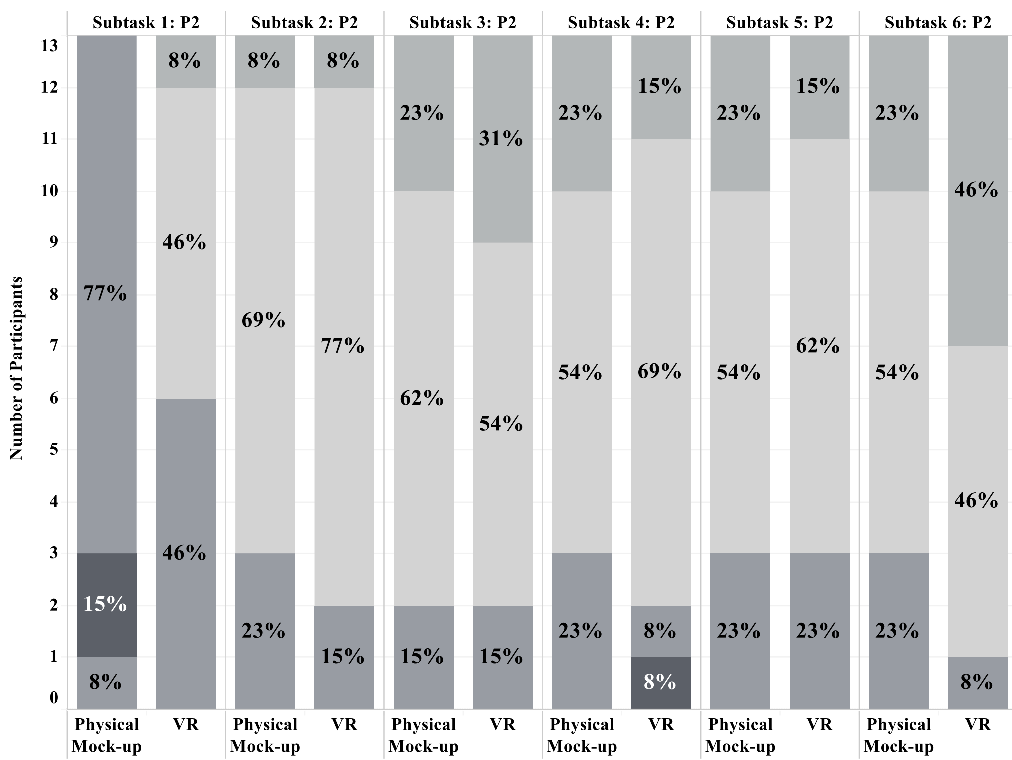


c. Key body posture P3.

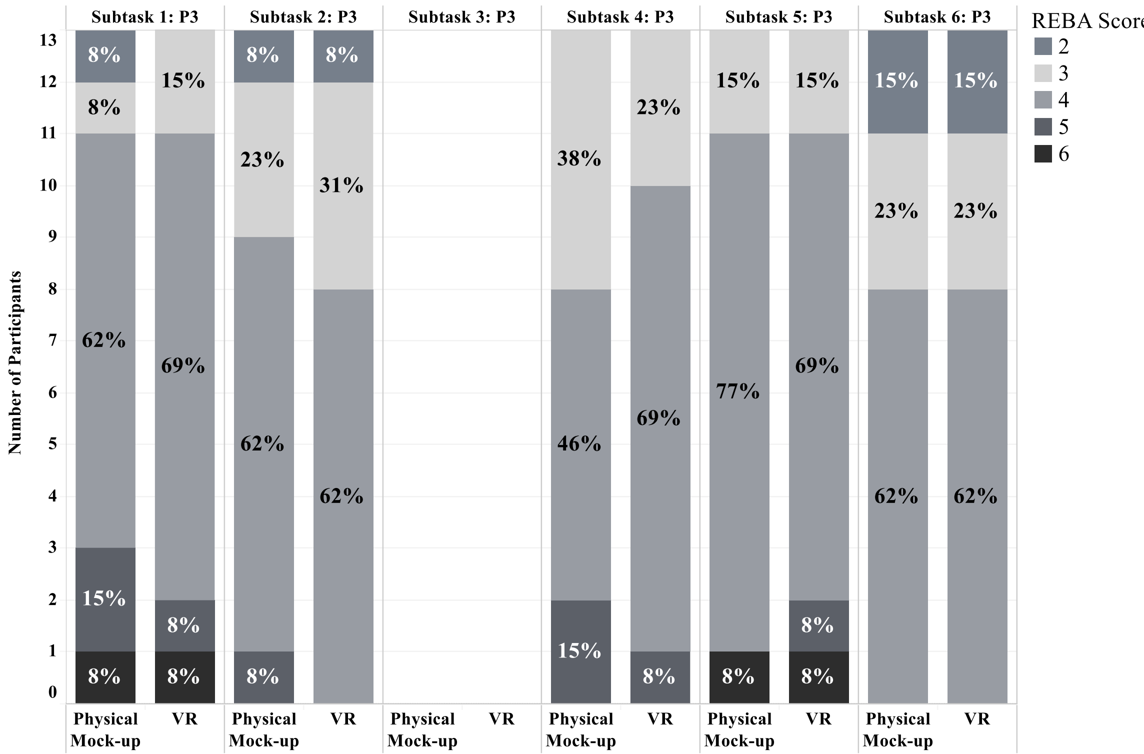
Figure 4.8: RULA scores per body posture, subtask, and environment.



a. Key body posture P1.



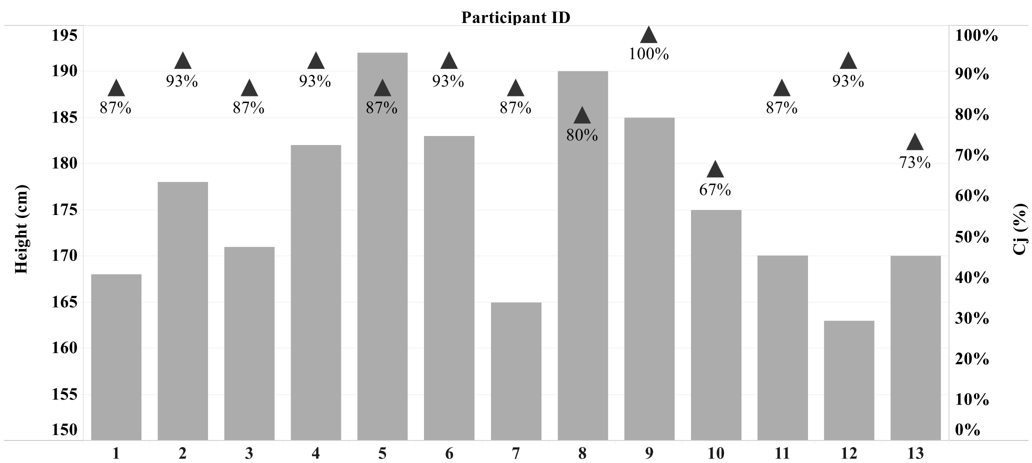
b. Key body posture P2.



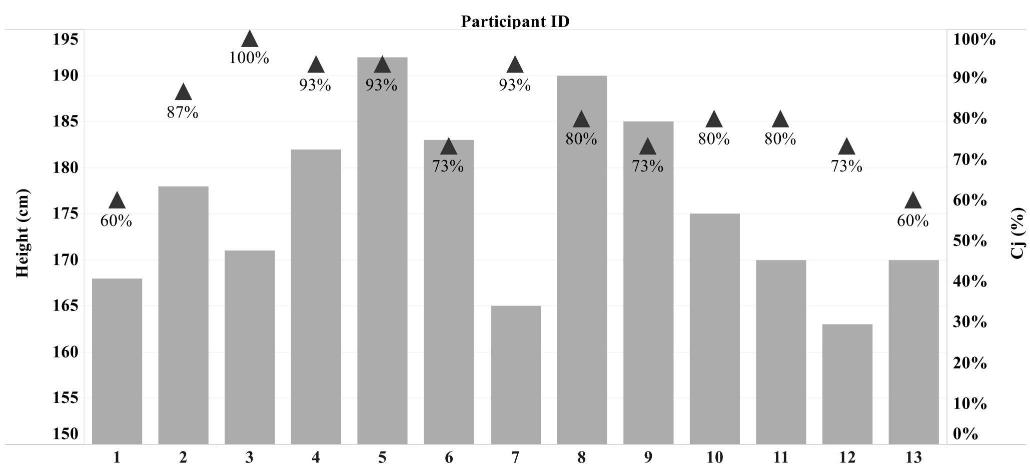
c. Key body posture P3.

Figure 4.9: REBA scores per body posture, subtask, and environment.

As illustrated in Figure 4.10, one participant (i.e., ID 9 in RULA and ID 3 in REBA) obtained an equivalent $RR_{i,p}$ and $RV_{i,p}$ in each of the key body posture of the six subtasks. Although one participant (i.e., ID 10) obtained a $\bar{c}_j$ (compatible scores per participant) of only 67% in RULA and two participants obtained a $\bar{c}_j$ (i.e., ID 1 and 13) of 60% in REBA (Figure 4.10), the average value of $\bar{c}_j$ in this study is found to be approximately 86% and 80% for RULA and REBA, respectively. Incompatibility of RULA and REBA scores per environment reflected on the $\bar{x}$RULA and $\bar{x}$REBA scores of each participant as shown in Figure 4.11. To verify the strength of the relationship between participant height and $\bar{c}_j$ calculated for both RULA and REBA (Figure 4.11), Pearson's correlation coefficient (ρ) was calculated; since ρ was determined to be equal to 0.14 and 0.22, respectively, a weak linear correlation was thus identified between participant height and these outcomes. In terms of $\bar{c}_j$, the results indicated that $\bar{c}_j$ varies significantly according to participant behaviour and motion preferences, as illustrated in Figure 4.12, which shows the lowest and highest RULA score of participants while performing Subtask 1-P3 and Subtask 3-P1. This finding underscores the importance of including ergonomic aspects of a task when providing training for workers. By standardizing how a task is performed, ergonomic risks can be limited to an acceptable level. Furthermore, the exposure to the remaining risks is expected to be consistent to all workers and within the same risk rating.

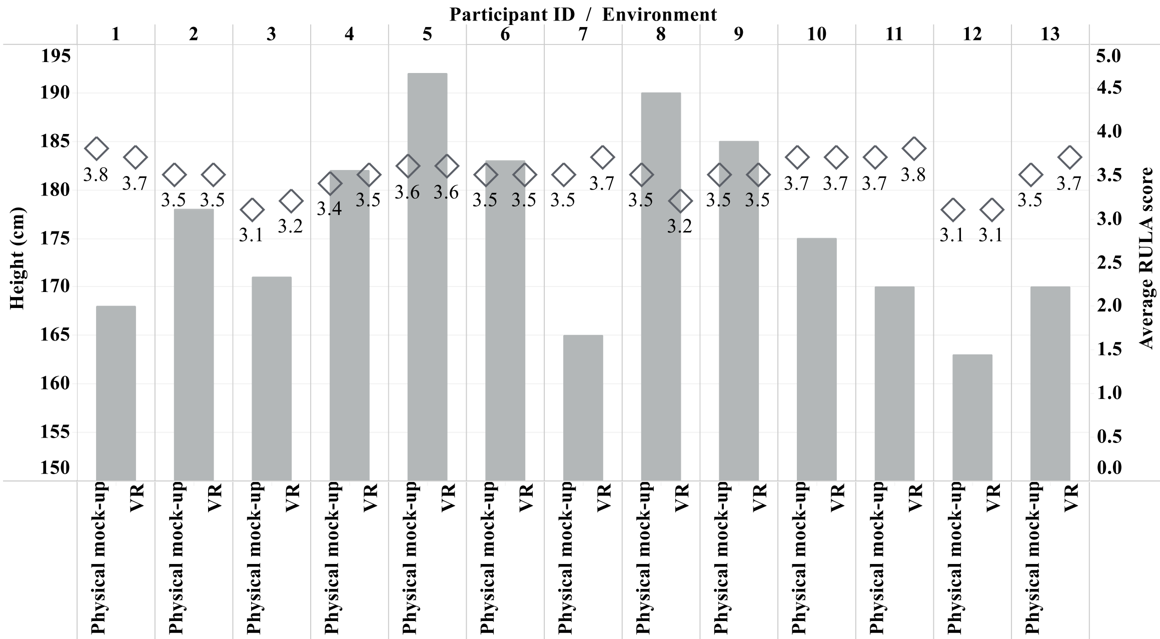


a. RULA.

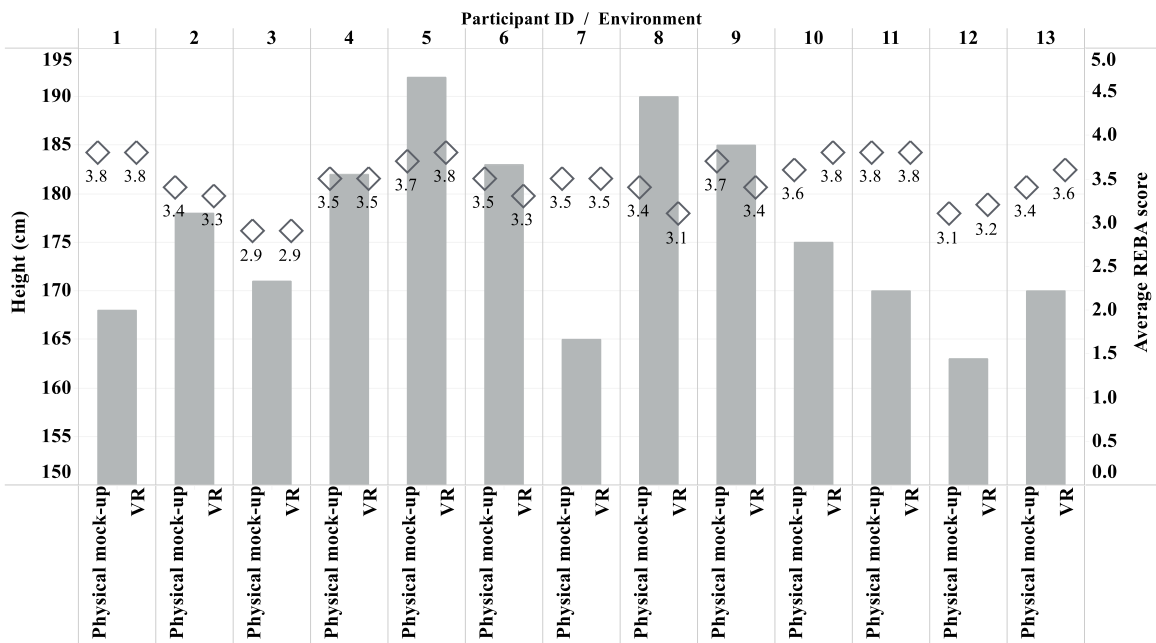


b. REBA.

Figure 4.10: Participant height (grey bar) and $\bar{c}_j$ (participants' compatible scores).



a. RULA.



b. REBA.

Figure 4.11: Average risk rating (diamond shape) per participant, environment, and participant height (grey bar).

a. Subtask 1-P3

(RULA = 3)

b. Subtask 1-P3

(RULA = 6)

c. Subtask 3-P1

(RULA = 3)

d. Subtask 3-P1

(RULA = 5)

Figure 4.12: Samples of variation in participant body movements during the experiment.

With respect to compatible RULA scores per key body postures of a subtask ($\bar{c}_i$), the highest $\bar{e}$ and second lowest $\bar{c}_i$ were found in the P3 of Subtask 5, as depicted in Table 4.3. This discrepancy resulted from the fact that a few values of $RV_{5,P3}$ are slightly higher than $RR_{5,P3}$, a phenomenon which is caused by side-bent neck combined with an arm rotation to the side of the body while performing the task in the VR application. In Subtask 6-P3, there were two scenarios of incompatible RULA scores: $RR_{6,P3} > RV_{6,P3}$ and $RR_{6,P3} < RV_{6,P3}$. In both scenarios, the primary contributor for this inconsistency was side-bent neck while performing the subtask, which was also the reason for this subtask's low $\bar{c_i}$ value. In terms of REBA, the highest $\bar{e}$ and lowest $\bar{c_i}$ were found in the P2 of Subtask 6 due to a few $RV_{6,P2}$ slightly lower than $RR_{6,P2}$. The reasons for these incompatible REBA scores were variation of neck, upper arm, and wrist joint angles.

Since both RULA and REBA assessments attribute the same score to joint angles within a certain range (Table 4.1) meaning that slightly different human body motions can lead to the same RULA and REBA scores, body joint angles were also analyzed per key body posture (Figure 4.13). The average body joints angles obtained in both real and virtual environment converged overall; for instance, the average joint angle of upper arm in the posture P2 was found to be 29 in both environments. On the other hand, the average joint angles of participants' neck in the posture P3 and upper arm in the posture P1 obtained the highest difference between the virtual and physical mock-up, a $\bar{d}$ equal to 12°; this discrepancy can be observed in Figure 4.13. Based on the analysis of joint angles, it is noted that the VR environment was more suitable to simulate movements of the neck (i.e., P1 and P2 postures), trunk (i.e., P1 posture), and upper arms (i.e., P2 and P3 postures), lower arm (i.e., P2 and P3 postures) and wrist (i.e., all the three postures). However, further investigation of body joint angles is required, preferable using a MOCAP system, to determine if VR is appropriated for analyzing human body joint angles. It is important to note that participants were standing with their legs in straight position; for this reason, the joint angles of both legs were not included in Figure 4.13.

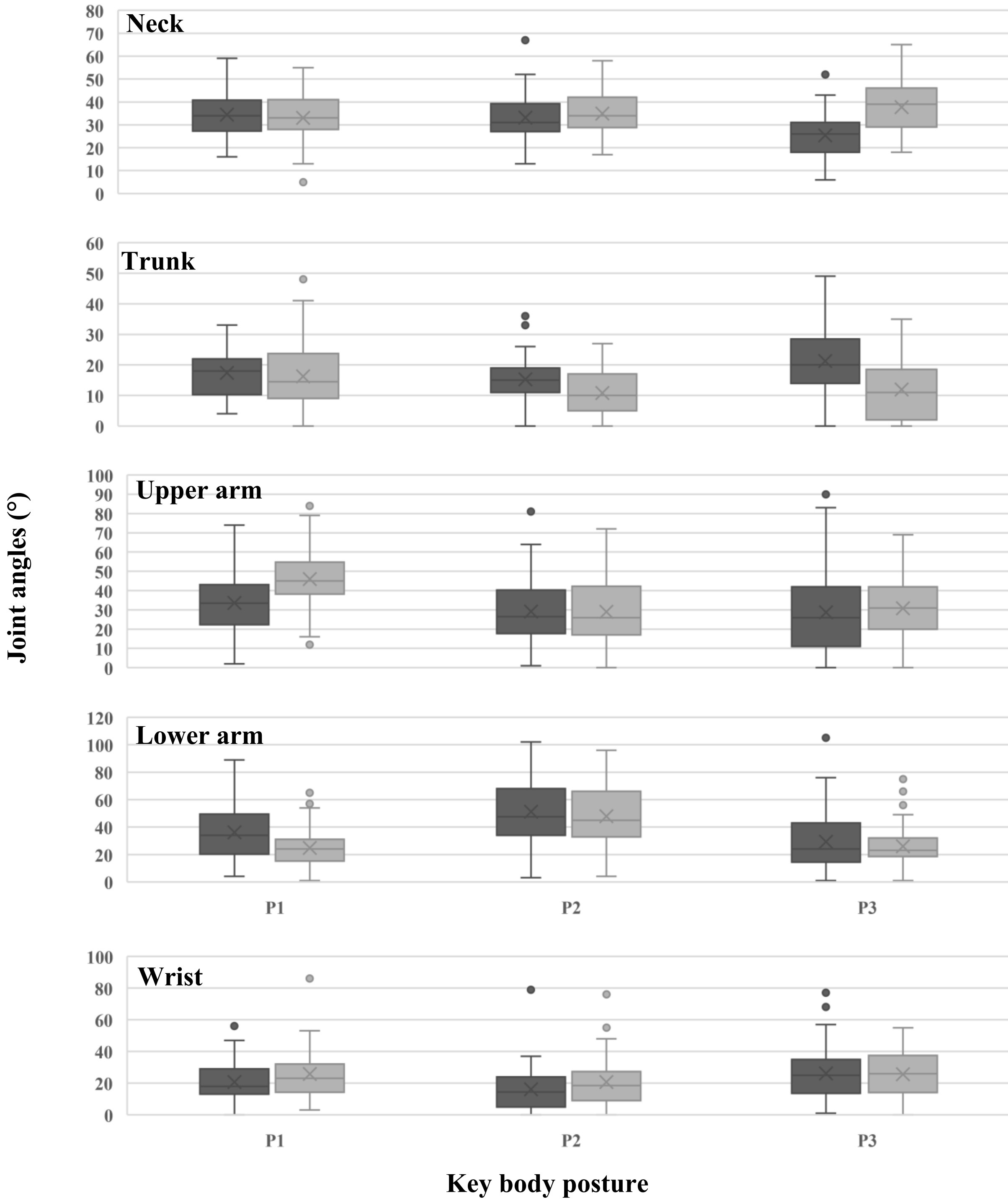


Figure 4.13: Joint angles per body posture and environment (dark-grey = physical mock-up; light-grey = VR).

Although most participants demonstrated neutrality in relation to H_{10} and H_{17}, which refers to the accuracy of the task and participants' body motions in the virtual environment, the $\bar{x}$RULA and $\bar{x}$REBA scores calculated for both environments were found to be relatively compatible overall. Moreover, fairly good linear correlation was verified between RULA and REBA scores calculated for both environments (VR and physical mock-up), $\rho = 0.78$ and 0.71, respectively. When the correlation of RULA scores was analyzed for each key body posture, results demonstrated that the VR application successfully simulated disassembling motions (P1), $\rho = 0.86$, which is the predominant motion of the task analyzed herein, and lifting (P2) motions were reasonably simulated as well, $\rho = 0.73$; however, positioning (P3) motions still require further investigation ($\rho = 0.63$). The correlation of REBA scores was also analyzed per each key body posture; ρ was found to be equal to 0.73, 0.64, and 0.68 for postures P1, P2, and P3, respectively. Therefore, it is verified that the correlation between RULA scores calculated in both real and virtual environments is stronger than the correlation between REBA scores.

These findings indicate that the VR application is sufficiently representative of the physical mock-up that the assessment of ergonomic risk ratings (i.e., RULA and REBA methods) can be accurately performed in a safe and controlled environment. Although both RULA and REBA obtained a good accuracy compared with the physical mock-up, the results indicated that the prediction of RULA scores using VR is slightly more precise. This finding underscores the need for future research to explore the use of VR for providing ergonomic risk ratings using several assessment methods. The conclusions drawn from this study are in agreement with the previous findings of Dias Barkokebas et al. (2020) and Peruzzini et al. (2019). Furthermore, the limitation identified in the study by Pontonnier et al. (2013), a significant discrepancy in RULA scores between real and virtual environments, is found to be overcome in the present study. However, due to the limited number of study participants, generalization of the results obtained in this study should be limited. To address this limitation, recruitment will be expanded in future studies in order to engage more participants.

In light of these findings, the VR-based ergonomic risk assessment methodology proposed in this study is deemed suitable for performing ergonomic analysis of manual handling operational tasks similar to the ones investigated herein. Therefore, the gap identified in the literature with respect to applying VR to evaluate workers' body movements in industrialized construction tasks for ergonomic risk rating analysis is addressed. Furthermore, the feedback provided by the participants of this study is applicable to the design of other VR applications, which will aid in the development of future ergonomics-related VR studies in other areas. For instance, it is noted that the VR application can be simplified for ergonomic risk assessment purposes providing that primary operational tasks, elements, and conditions are included in the VR environment; however, simplification of the application can result in participants feeling an incongruity between their body movements in the virtual versus real environments, as per the findings of our experiment. This is a significant outcome of the questionnaire, especially for cases in which VR is being used to provide training to workers or to assess user's fatigue and/or perception of the virtual environment. In such scenarios, not only should the virtual environment be aesthetically similar to the real-world, but it also should mimic real-world tasks to a sufficient degree that participants consider their body motions to be reasonably similar in both environments. In addition, the questionnaire also assisted in verifying whether the approach pursued to develop the VR application resulted in a satisfactory representation of the real environment in terms of aesthetics, dimensions, and user interactions based on the perspective of participants, and it also aid in evaluating if the designed VR application provided a good experience for the user.

4.5. Limitations and Future Work

The task explored in this study did not include a considerable variety of body motions, as the relatively simple nature of the task facilitated the calculation of RULA and REBA scores based on post-analysis of videos recorded during the experiment, the use of a MOCAP system is recommended to be applied in more complex tasks. Still with respect to ergonomic risk analysis, the fact that body joint angles were derived by a single individual is another limitation of this study; this limitation will be resolved in future studies by integrating MOCAP systems to the method proposed herein. Although the sample size of the participants in this study is in line with previous research in this area (Aromaa and Väänänen 2016; Maline and Pretto 1994; Paravizo and Braatz 2019; Peruzzini et al. 2019; Pontonnier et al. 2013), it is still limited. To address this limitation, the recruitment of participants will be expanded in the future to increase the engagement of more participants, and, thus, potentiate the generalization of results obtained. A within-subject design was chosen as the research method to design the experiment which results were presented in this paper; this methodological approach is suitable to the experiment conducted herein since intellectual skills were not relevant to the analysis performed and as it also addresses issues with sample size of participants. However, in future studies, other methods of experiment design such as between-subjects and the random distribution of the sequence of experiments (i.e., VR and real) between participants will be explored. In addition, the interactions in the virtual environment between a subject's two hands, as well as between hands and tools, need improvement in order to better represent the actions in the physical mock-up; although results indicated that this drawback did not impact on the RULA and REBA scores, this limitation will be also addressed in future studies to improve participants perception of the task being simulated. Although this study did not focus on acquiring information related to the time required to conduct tasks in different environments (VR and real), based on the analysis of the recorded videos, it is observed that tasks were performed more rapidly in the VR environment, which would impact on the results of ergonomic analysis which are not based on key body postures.

In this context, a future direction for research is to extend the investigation to include: (a) use of a MOCAP system to automatically collect information on body motions in an accurate manner thus reducing errors due to subjective bias and allowing the investigation of more physically-demanding tasks and of human body joint angles; (b) simulation of industrialized construction tasks with more physically-demanding motions such as squatting and bending, and involving lifting of objects weighing more than 2 kg; (c) design of VR applications to simulate tasks in which participants are required to interact more intensively with materials and equipment; and (d) other experimental design methods.

4.6. Conclusion

This study proposes a methodology to perform ergonomic risk rating assessment of workstation design in a safe and controlled environment using VR to reduce the need of physical mock-ups to evaluate operational tasks in industrialized construction. To verify the effectiveness of the proposed methodology, a research experiment which requires participants to perform the same task in both real and virtual environment was conducted with 13 participants. Two ergonomic risk assessments were performed by applying the RULA and REBA methods in both environments. The results demonstrate that VR is applicable to ergonomic risk assessment of tasks similar to the operational task investigated in this study, with an accuracy rate of 86% and 80% in representing the physical mock-up (based on a comparison of the respective RULA and REBA scores, respectively, calculated by observing participants in the physical mock-up and the VR application).

Hence, this study fulfills the research gap identified in the introduction of this paper by (a) investigating manual handling tasks in industrialized construction operations using VR, (b) providing an updated comparison of RULA and REBA scores calculated based on the observation of a task completed in a physical mock-up and a VR application, (c) reducing the incongruity between RULA scores calculated in the physical mock-up and the designed VR application, (d) verifying the effectiveness of the proposed methodology to conduct ergonomic risk assessments using VR.

In addition to the comparison of RULA and REBA scores, this study presents data collected by a questionnaire designed to obtain participant feedback on the developed VR application. Based on the responses of the questionnaire, it is verified that participants felt safe, comfortable, and engaged while immersed in the developed VR technology. Nonetheless, potential improvements to the VR application are also identified based on the feedback received. These include improving the representation of hand motions, and accounting for challenges faced in the physical mock-up (e.g., imbalanced parts in the assembly causing issues during execution of the task in the physical mock-up). This feedback can also inform the design of future VR applications in other research areas. The future direction of this study, moreover, is to (a) incorporate MOCAP technologies to assist in the calculation of RULA and REBA scores, and human joint angles, and (b) develop VR applications to simulate operational tasks that require a broader range of body motions and interactions as well as the lifting of objects weighing more than 2 kg.

4.7. Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

4.8. Acknowledgments

The authors appreciate the technical writing assistance of Jonathan Tomalty and Kristin Berg. In addition, the authors express their gratitude to Dr. Mohamed Al-Hussein for his supervision, Tianyu (Jayden) Jiang, Jin (Judy) Liu, and Val Sirbu for assisting in the gameplay scripting and in designing the 3D scenes used in the VR application, Chelsea Ritter for insights during the development of the VR application, Anas Itani for assisting with the physical mock-up, as well as to all volunteers who participated in the experiment. This work was supported by the Natural Sciences and Engineering Research Council of Canada (NSERC) Discovery Grant [grant number RGPIN-2019-04585] and the University of Alberta.

CHAPTER 5: VR–MOCAP-ENABLED ERGONOMIC RISK ASSESSMENT OF WORKSTATION PROTOTYPES IN OFF-SITE CONSTRUCTION[3]

5.1. Introduction

According to the Canadian Centre for Occupational Health and Safety (2017), the primary causes of work-related musculoskeletal disorders (WMSDs) are forceful exertion, awkward body posture, and repetitive motions. Workers in off-site construction facilities, despite benefiting from the controlled conditions in a factory environment and from the provision of semi-automated and automated workstations, are still subject to a high degree of physical demand (Public Services Health & Safety Association 2010). Indeed, the standardization of products and processes in a production line setting results in repetitive motion, which increases muscular tension even in the absence of awkward body postures and regardless of the level of force required (Golabchi et al. 2016). In this context, workstation design and facility layout have a significant bearing on worker exposure to the risk of developing a WMSD due to the concentration of processes at the workstations. On the other hand, this concentration of processes at the workstations presents an opportunity to mitigate worker exposure to the risk of developing a WMSD through workstation design solutions. Thus, to reduce long-term exposure to risks related to WMSDs, it is crucial to improve workplace ergonomics by assessing and mitigating ergonomic risks early in the workstation design stage.

[3] The manuscript appearing as Chapter 5 of this thesis is published as Dias Barkokebas, R., Al-Hussein, M. and Li, X. (2022). "VR–MOCAP-enabled ergonomic risk assessment of workstation prototypes in off-site construction". *Journal of Construction Engineering and Management*, 148(8), 04022064-1– 04022064-17.

Traditionally, a workplace ergonomic assessment is based on subject observation, which involves observing workers, either on site or via recorded videos, performing tasks in their workplace (Peruzzini et al. 2019). However, this traditional method used to collect human body motions has limitations since it is laborious and error-prone due to observer bias and occlusion issues, in addition to the fact that it often requires an ergonomist or a field specialist (Diego-Mas et al. 2015). Furthermore, in this scenario, workstations are already operational, thus any alteration to workstation design results in productivity losses and increased implementation time and costs (Peruzzini et al. 2019). To overcome these limitations, the conventional practice is to identify ergonomic risks during the early design phase using physical prototypes of the workstation designs (Jia et al. 2011), which requires the commitment of major resources (Azizi et al. 2018). Therefore, the investigation of alternative prototyping methods with the aim of quickly evaluating workstation designs in terms of ergonomics while minimizing iterations with physical prototypes is critical to reduce the time and cost required to develop an improved design.

To achieve a robust ergonomic analysis at any stage of design development, simulating and virtually modelling working scenarios are suggested as an alternative approach to physical prototyping (Peruzzini et al. 2020a). In particular, virtual reality (VR) produces immersive computer-generated virtual environments in which users experiment and evaluate prototypes based on interactions at real scale (i.e., 1:1), which is also the primary advantage of physical prototyping (Wolfartsberger 2019). Furthermore, since the user's interaction with the environment is primarily virtual, adjustments to a design can be incorporated in the virtual environment and an updated workstation design can be quickly re-assessed, thus, speed and flexibility are added to the design development phase (Seth et al. 2011). The application of VR in the construction industry is explored in a variety of areas such as virtual prototyping (Deviprasad and Kesavadas 2003; Huang et al. 2007; Li et al. 2012b), training on construction equipment and tasks (Barkokebas et al. 2019; Li et al. 2012a; Rezazadeh et al. 2011), and ergonomic analysis (Battini et al. 2018; Dias Barkokebas et al. 2020; Hadikusumo and Rowlinson 2002). However, according to the review of existing literature performed by Davila Delgado et al. (2020), research is still needed in order to realize the full implementation of VR in the architecture, engineering, and construction sectors.

In this context, this study proposes a VR-based simulation method by which ergonomic risk assessment can be applied during the prototyping phase of workstation design development. In this scenario, the need for physical workstation prototypes is reduced through the simulation of real-world tasks in a virtual and immersive environment, thereby reducing the cost and time required to modify and improve a workstation design before it is implemented on the production line. In addition, in the proposed method, human body motion data is acquired through a motion capture (MOCAP) system to increase the accuracy of the data collection for the purpose of ergonomic analysis. The feasibility and reliability of the proposed method is verified by a practical application that explores two design options for a workstation at which hardware is installed on window frames. An anticipated outcome of the proposed VR–MOCAP-enabled ergonomic risk assessment method is that it will provide designers with quantitative and qualitative data on the ergonomic risks inherent in their design giving an opportunity for design improvements during prototyping phase, thereby reducing ergonomic risks through design solutions.

5.2. Background

5.2.1. Body Motion Data Collection

To collect body motion data for ergonomic analysis purposes, several methods are available; however, there remains limitations closely related to their real-life application in off-site construction (David 2005). To evaluate the potential risks that workers may encounter in their workplace, pertinent information, such as body joint angles, needs to be acquired accurately and efficiently, but this can be time-consuming and error-prone, depending on the chosen method of data collection (Li et al. 2018). Most of the existing ergonomic risk analysis methods can be classified as self-report, observational, physiological measurement (i.e., direct, indirect, digital, and biomechanical), or digital. Self-report involves the use of questionnaires, interviews, and diaries; the interpretation of their results can be imprecise due to the perceived consequences of reporting a risk and due to inter-rater discrepancies of interview results (Li et al. 2018). Observational methods collect detailed physical data based on subject observation, either directly on site or by viewing recorded video footage, and are based on a post-analysis of workers' behaviours (Roman-Liu 2014). The limitations of these methods stem from the fact that they are time-consuming, error-prone due to inter-rater discrepancies, and they are based primarily on postures (Wang et al. 2015). Physiological measurements focus on body joint angles, force loads, muscle activity, etc. Direct-based physiological measurements, such as MOCAP systems, acquire body motions in real time using sensors or markers that are attached to the human body (Bortolini et al. 2018). There are two primary types of MOCAP systems: optical and non-optical. Optical MOCAP systems are composed of markers and several cameras, and since they rely on video cameras capturing the positioning of sensors, these systems are susceptible to obstruction due to operational motions (Bortolini et al. 2018). Non-optical systems such as inertia systems are composed of small inertial measurement units (IMUs) that use gyroscopes, magnetometers, and accelerometers to estimate body movements without the need for a visual field (Fletcher et al. 2018), and because non-optical systems use wireless communication, inertial MOCAPs are portable as long as the sensors are within the wireless range. Indirect measurements, in contrast, use computer-vision methods and Kinect range cameras to collect body motions (Ray and Teizer 2012). As the range cameras require an unobstructed visual in order to acquire data, these methods are prone to error due to occlusion and illumination issues, and data post-processing can be time-consuming. Biomechanical analysis uses computer software to perform the analysis based on the prediction of the subject's reach, strength, metabolic rate, etc., and thus the analysis is not based on real body motion data (Feyen et al. 2000). Alternatively, digital measurement derives body motion data from three-dimensional (3D) animations modelled to represent real-world tasks (Li et al. 2018). To employ digital measurement methods, 3D modelling skills and initial information on body motions are needed to develop the 3D animations (Li et al. 2018). In light of the limitations of these methods and as pointed out by Wang et al. (2015), there remains an opportunity for investigating an effective approach to collect body motion data for ergonomic analysis purposes in a controlled environment such as a laboratory setting where human–product interactions can be simulated without causing interruptions to the real workplace.

5.2.2. Virtual Reality Applied to Ergonomic Risk Assessment

As noted in Table 5.1, relatively few studies have investigated the application of VR to ergonomic analysis in a factory environment; moreover, those that are available do not focus on the off-site construction industry (please refer to the "engineering field" columns in Table 5.1). In addition, these studies employed various methods for various purposes: mixed prototyping was used to conduct analyses (Peruzzini et al. 2019; Vosniakos et al. 2017); an existing computer software tool such as DELMIA Ergonomics was used to calculate RULA scores (Azizi et al. 2018; Peruzzini et al. 2019); a questionnaire/checklist was employed (Aromaa and Väänänen 2016); experiments were conducted either in the factory to validate the design of a virtual workstation (Caputo et al. 2018a; b) or entirely in a virtual environment where both workers and tasks were virtual elements

(Azizi et al. 2018); VR was used to investigate fatigue (Azizi et al. 2018); information was derived on human body motion (i.e., estimation of joint angles) based on the frame-by-frame observation of a video recorded in Unity 3D software (Vosniakos et al. 2017); and a theoretical methodology was proposed in which application and effectiveness was not demonstrated through a case study, such as in Battini et al. (2018), for example. Pontonnier et al. (2014) stated that ergonomic studies of assembly tasks using VR still required further investigation, indicating opportunities for future research on this topic. A similar conclusion was provided by Vosniakos et al. (2017) which stated that basic motions and interactions were successfully simulated in the VR environment; however, there was still opportunity to improve the fidelity of the motions obtained from the VR simulation. Caputo et al. (2018b) indicated that evaluating the European Assessment Worksheet (EAWS) index in a VR environment yielded a more conservative analysis, which can be an asset during the design phase of workplaces. Another study proposed a protocol analysis for the assessment of industrial workstations in which both Rapid Upper Limb Assessment (RULA) and Rapid Entire Body Assessment (REBA) were recommended as units of measurements for ergonomic analysis (Peruzzini et al. 2016). Both REBA (Hignett and McAtamney 2000) and RULA (McAtamney and Corlett 1993) are existing ergonomic risk assessment tools that provide a quantitative risk score based on a worker's posture; they are frequently used in research studies. RULA and REBA were chosen for the ergonomic risk assessment conducted as part of the present research.

Table 5.1. Comparison of previous studies that explored VR with MOCAP for ergonomic analysis.

Reference	Engineering field				MOCAP system			Ergonomic analysis				
	I	M	A	AT	D-O	D-I	I-K	RULA	REBA	Self-report	Posture	Other
Pontonnier et al. (2014)	■				■			■				■ Muscle activity
Aromaa and Väänänen (2016)		■			■					■		
Vosniakos et al. (2017)			■				■	■	■	■		
Azizi et al. (2018)	■							■				
Caputo et al. (2018a)				■		■					■	■ EAWS
Caputo et al. (2018b)				■		■					■	■ EAWS

Battini et al. (2018)	■		■	■	■
Peruzzini et al. (2019)	■	■		■	

Note: abbreviations used in the table: I = Industrial; M = Mining; A = Aerospace; AT = Automotive; D-O = Direct measurement–Optical; D-I = Direct measurement–Inertia; I-K = Indirect measurement–Kinect.

Although previous studies have already explored the integration of VR and MOCAP, there is still a need for a method in which a holistic ergonomic analysis considering multiple aspects of ergonomics (e.g., motion, reachability of elements, and users' perception of mental and physical workload) is conducted using VR, especially as applied to the analysis of manufacturing tasks in the construction industry. Off-site construction facilities differ from other factory environments (e.g., automotive manufacturing) in the sense that operational tasks are still labour-intensive despite the use of semi-automated or automated machinery. For instance, workers in these facilities often transport materials manually from the storage area to the workstation. In comparison to traditional construction, muscular tension is intensified in off-site construction production lines as a result of repetitive motion due to the standardization of the processes. The proposed VR–MOCAP-enabled ergonomic risk assessment method has the potential to allow the simulation of entire tasks; to provide semi-automated data post-processing so researchers can quickly analyze multiple options of improvements proposed for a production line; and to obtain body motion data in a controlled environment, which reduces the frequency of work interruptions. Ultimately, the proposed method is presented as an alternative tool for evaluating workstation design options based on real motion data to improve workplace ergonomics, thereby reducing injury rates and helping to mitigate the risks of developing a WMSD in the off-site construction industry.

5.3. Research methodology

This study applied an experimental research methodology to propose and determine the feasibility of a method for assessing ergonomic risks of workstations based on the human factors that are collected using an inertia MOCAP system while subjects are simulating an operational task in a VR environment. As shown in Figure 5.1, the experimental research methodology involves eight steps, as follows: (1) identify problem(s); (2) formulate hypothesis or proposition; (3) determine objectives, variables, and conditions; (4) design experiment; (5) conduct experiment and collect data; (6) analyze data; (7) interpret results; and (8) communicate findings (Anderson and Whitcomb 2017). As shown in the Introduction and Background sections, it was identified through a review of existing literature that workers are exposed to ergonomic risks in off-site construction facilities primarily due to deficiencies in the design of workstations design and due to the highly physically demanding nature of the tasks being performed (e.g., motion repetition). In addition, there remains a deficiency in methods to mimic and anticipate, in a laboratory setting, the body motions required to undertake an entire activity with the objective of identifying and reducing ergonomic risks to facilitate an analysis based on real body motion data in early design development. In Step 1, the aforementioned problems were identified as problems to be addressed in the present study. In Step 2, the proposition on which the present study is built was defined as follows: *To improve workstation ergonomics during the workstation design stage, integrating virtual reality (VR) with ergonomic analysis in a laboratory setting is a method that can be used to proactively simulate and anticipate ergonomic risk in an off-site construction setting*. To investigate this proposition, in Step 3, the primary objectives of this study were defined as proposing a VR–MOCAP-enabled ergonomic risk assessment method and verifying the feasibility of deploying the proposed method by way of a practical application. As such, this study had one independent variable, the environment where tasks were completed, with two conditions: physical prototype and VR simulation. The completion of the task using the physical prototype provided a benchmark to which the results obtained from the VR environment were evaluated in the comparative analysis performed in Step 6 of the research methodology. In Step 4, the experiment was designed as a within-subject experiment, which means that all participants were exposed to all the conditions being explored. As such, differences between participant performance and behaviour across the two environments were observed (Charness et al. 2012). In Step 5, experiments were conducted to demonstrate a practical application designed to determine the feasibility of the proposed method. During the experiments, participants' body motion data were collected with a MOCAP system, videos were recorded, and responses to a questionnaire were acquired. To ensure that the performance in one environment did not influence the performance in the other (i.e., due to fatigue, carryover effect), the physical and VR experiments were carried out several months apart from one another. In Step 6, the collected body motion data were analyzed focusing on RULA, REBA, joint angles, and maximum reach (i.e., reachability analysis). In addition, subjective data from the questionnaire were verified based on the average rating of each question to provide additional insights regarding the perception participants had of the task and their interactions with the VR environment, which is valuable information during the development of the proposed method. Commonly, in within-subject experimental design, the data are averaged for analysis purposes (Fellows and Liu 2008); nonetheless, data from individual participants were also used during Step 6 to provide detailed information about the investigated task. The results were interpreted, and the generalization of findings was performed in Step 7. The present study communicates the proposed method and the findings obtained through its practical application including both quantitative (e.g., REBA and RULA scores, joint angles, and reachability analysis) and qualitative (e.g., questionnaire responses) data, thus addressing Step 8.

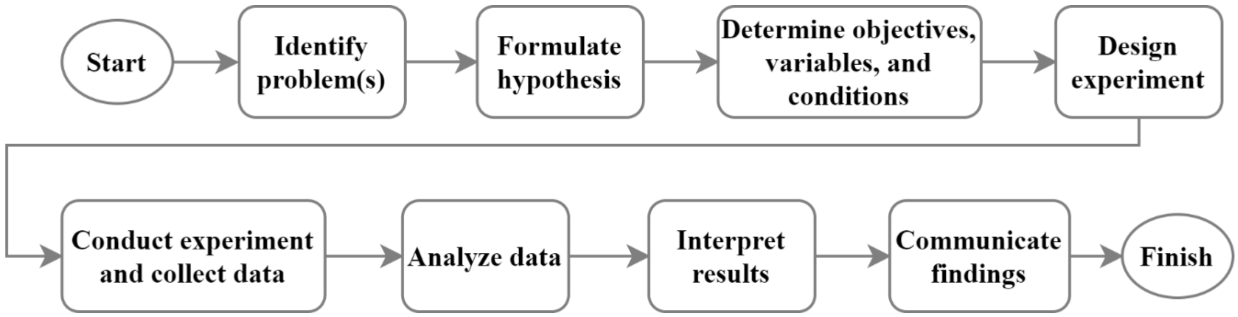


Figure 5.1: Overview of research methodology.

5.4. Proposed VR–MOCAP-enabled Ergonomic Risk Assessment Method

The inputs of the proposed method include thorough information on the task to be simulated such as workstation design and dimensions, sequence of activities, and tools/procedures needed to perform the task as well as the participants' anthropometric information needed for the MOCAP software, and historical injuries that may affect a participant's mobility. As illustrated in Figure 5.2, the development of the proposed method requires input from both task and participants while comprising the following five primary phases: (1) identification of key design parameters, (2) identification of key body motions, (3) VR model design, (4) data acquisition covering body motion data and questionnaire responses, and (5) data analysis. This holistic analysis combines objective (i.e., body motion data) and subjective data (i.e., questionnaire responses), and uses different techniques of data collection (e.g., MOCAP and VR) to allow ergonomic analysis to occur in the design phase based on multiple criteria such as total RULA and REBA scores, maximum reaching, and mental and physical workload. The data collection and analysis techniques are further detailed in this section. The last three phases of the proposed method can be followed in a continuous loop (represented as a dashed line in Figure 5.2) until ergonomic risks are reduced. As such, this study is expected to produce the following outcomes: ergonomic risk scores, an evaluation of the workstation design in terms of ergonomic risks, identification of the most physically demanded body segments, and participants' perception of the VR model and the physical and mental workload associated with the task.

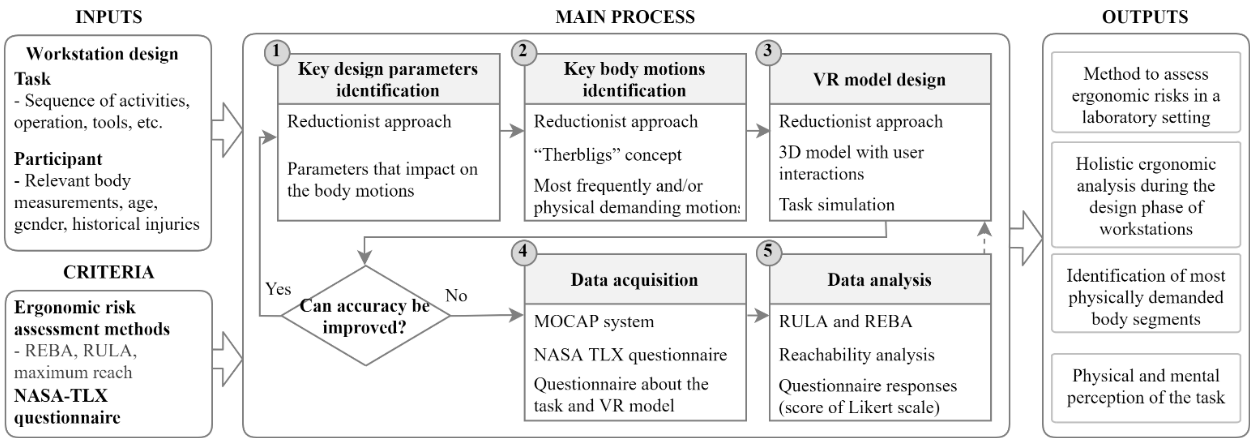


Figure 5.2: Overview of proposed method.

This study expands the research of Dias Barkokebas and Li (2021) and Dias Barkokebas et al. (2021) by adding another layer of complexity and accuracy to the aforementioned studies in that the present study incorporates the use of an inertia MOCAP system to collect body motion data, indicated as a direction of future studies in Dias Barkokebas and Li (2021), while the study also includes ergonomic assessment in terms of reachability analysis and perception of physical and mental workload.

5.4.1. Identification of Key Design Parameters

In Phase 1, the workstation design under study and a description of its operation task were reviewed to identify the key design parameters that have an impact on the body motions required to complete the task. In cases where a new workstation is designed to replace an existing one, observation of the current process is suggested as a means to acquire information on key design parameters. Examples of such parameters are the angle and height of the work surface area, and the vertical and horizontal distances that need to be reached to grasp materials and equipment. This information is essential in terms of simulating a real operation task when applying a reductionist approach in which a simplified version of the task is explored. In the reductionist approach, a system is divided into components and specific components are investigated to represent the entire system (Salmon et al. 2017). This approach is applied in Phases 1, 2 and 3 of the proposed method.

5.4.2. Identification of Key Body Motions

In Phase 2, key body motions were identified to aid in the verification of the accuracy of the VR simulation and to allow a detailed ergonomic assessment of the most frequently performed and/or most physical demanding motions. It is important to determine these motions so that participants' interactions with the virtual workstation can be designed to be sufficiently representative of the physical workstation such that these key motions are identifiable whether the participant completes the task using the VR prototype or the physical prototype. Therbligs are applied to deconstruct entire motions (including move-to-posture and posture) and tasks into thirteen basic motions such as reach, move, transport, etc. (Ferguson 2000; Meredith 1953). As such, therbligs assist in the detection of inefficient motions and fatigue-prone motions. The therblig concept was applied in Phase 2. The key body motions and therbligs that were identified by reviewing the description of the task were reassessed once body motion data was collected.

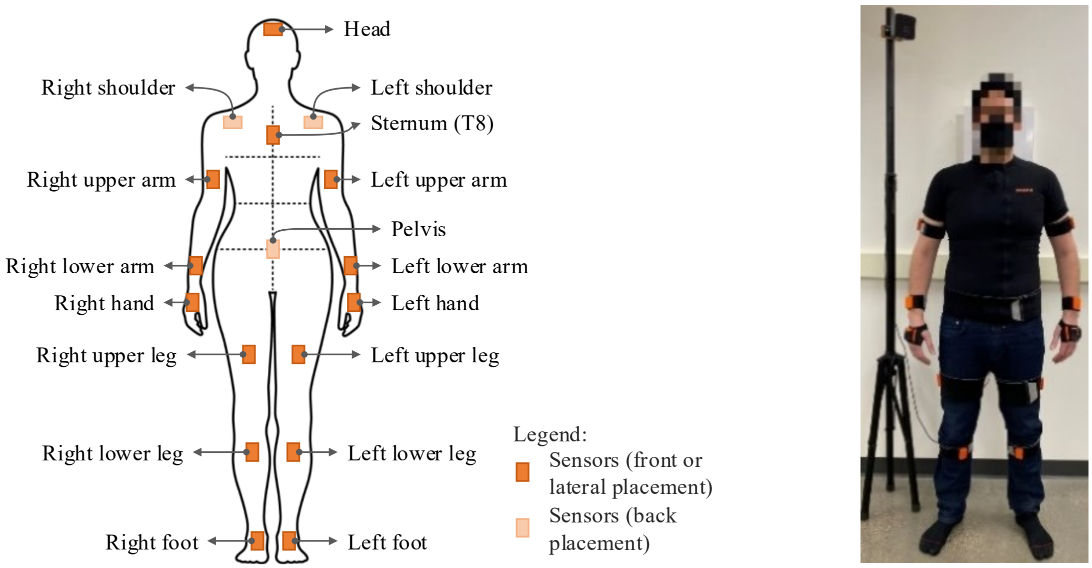
5.4.3. VR Model Design

In Phase 3, VR models were designed to simulate workstation design options being developed for an off-site construction facility. With respect to the VR environment, an HTC VIVE VR system was used that includes a headset, two wireless hand controllers, and two wireless base stations.

Unreal Engine was chosen to create these models due to its capabilities of using Blueprint Visual Scripting to develop realistic virtual environments (Paravizo and Braatz 2019). First, 3D models were created on Autodesk Maya based on detailed information on workstation design options. Then, these 3D models were imported into Unreal Engine (version 4.24.1) where user interactions were defined with the intent to simulate motions inherent to tasks associated with the investigated workstation, particularly the identified key motions. These motions include reaching above shoulder height, bending forward, and lifting objects weighing less than 2 kg (4.4 lb), which is the maximum weight that can be lifted without increasing the load score by 1 in the RULA method. The proposed method simulates an off-site construction task entirely in the virtual environment, meaning that mixed reality is not used, thereby lifting objects weighing more than 2 kg is not accounted for in the proposed method since the weight of lifted objects influences the risk assessment. An essential aspect that requires attention when designing VR models for ergonomic purposes is ensuring that objects are placed in the exact same position in the VR application as they would be in the physical workstation. Small differences in the locations of objects have an impact on the body motions of participants, in particular those performed with the arms, thus influencing the accuracy of reachability analysis and total RULA and REBA scores. There are two possible approaches to follow in order to model the grasp motion, which is critically important during VR model development: there approaches, (a) participants simply press and release the trigger button to grasp and hold an object, or (b) participants are required to continue pressing the side buttons while holding an object in the virtual environment. Based on the results of previous studies conducted by the authors (Barkokebas et al. 2019; Dias Barkokebas and Li 2021), approach (b) was chosen for the method proposed herein. Throughout the design phase of the VR applications, rounds of tests were conducted to ensure that these applications encompass both the existing real-world interactions, and that the virtual workstations were modelled as per the design specifications. The method proposed by Dias Barkokebas and Li (2021) for developing VR models for ergonomic risk assessment was followed to conclude Phase 3 of the proposed method.

5.4.4. Data Acquisition

With ethics approval, research experiments were conducted to collect participants' body motions while they were working at the workstation being prototyped in Phase 4. An inertia MOCAP system—Xsens MTN Awinda—was used to collect participants' body motions while they were completing the investigated task. The same MOCAP system was used in the physical and VR prototypes to ensure that the body motion data was not biased due to system changes. The MTN Awinda consists of seventeen IMUs that are attached to the human body as detailed in Figure 5.3. In order to estimate body motions accurately, participant information such as height, foot length, and arm span were measured to be used as input in the Xsens MVN Analyze 2020.0 software. In addition, the MOCAP system was calibrated for each participant prior starting the experiment. To perform this sensor-to-segment calibration, each participant was asked to stand in a known pose (i.e., neutral pose) and to complete a known motion (i.e., walking back and forth in a straight line). The calibration was only accepted if its estimated quality was indicated as "good", the highest level of calibration quality in the MVN Analyze 2020.0 software. In addition to the MOCAP system, video cameras were also used to record videos during the experiment to assist in the event of inconsistent data from the Xsens sensors. An online questionnaire was designed using Google Forms to measure perceived comfort by applying the six categories of questions from the NASA Task Load Index (TLX) (Hart and Staveland 1988) and to verify whether the designed VR model elicited a good user experience. The six questions pertaining to the NASA-LTX method were answered using a 7-point scale (i.e., very low = 1, very high = 7) to evaluate the required mental and physical activity load, the temporal demand of the task, the level of difficulty experienced in accomplishing the task, how successful participants were in accomplishing the task, and how frustrated they were during the task. The remaining twelve questions followed a 5-point scale focusing on the visual and practical aspects of the VR model.



a. Schematic position of sensors　　b. Participant with sensors

Figure 5.3: IMUs used to capture body motion information.

5.4.5. Data Analysis

By analyzing the data generated by the MOCAP and the recorded videos, the participants' body joint angles were determined during Phase 5. The raw data extracted using the Xsens MVN Analyze software contained information on 66 joint angles, including horizontal and vertical axis, and its output frame rate was 60 Hz. After cleaning and analyzing the data to check for inconsistencies, only information relevant to REBA, RULA, and reachability analysis was retrieved (i.e., 20 angles). During the data analysis, left and right sides, rotation, lateral bending, twisting, and arm movements across the body midline or out of the body line were identified and evaluated separately. The questionnaire responses were analyzed based on the distribution of responses on the Likert scale and on the average scores.

5.4.6. Risk Assessment

In Phase 5, ergonomic risk ratings were identified using the two previously mentioned risk assessment methods. Both REBA and RULA accurately provide a qualitative risk level based on a quantitative score as follows: for RULA, 1–2 = negligible, 3–4 = low, 5–6 = medium, and 7 = high (McAtamney and Corlett 1993); while for REBA, 1 = negligible, 2–3 = low, 4–7 = medium, 8–10 = high, and 11–15 = very high (Hignett and McAtamney 2000). Moreover, as both methods consider body posture, force load, coupling conditions, and repetition when calculating a risk score, the primary reasons for WMSDs in manufacturing tasks in the off-site construction are completely covered by these assessment methods. Both methods have distinct metrics to evaluate risks on the lower arm, wrist, neck, and trunk, and only REBA assesses leg angles. RULA and REBA attribute sub-score per body segment based on the range of joint angles. To identify the most physically demanded body segments, RULA and REBA sub-scores were compared. Given that the task is analyzed as a continuous operational task, the body motion data is in the form of a time series where there are multiple data points for each participant. Because the execution time varied depending on whether a task was completed in the VR environment or the physical prototype, plotting the risk score per body segment of all participants for a continuous operational task was not practical since participants could be performing a different motion during any specified time frame. For this reason, RULA and REBA sub-scores per body segment were analyzed using the average sub-score calculated for the entire task and for the defined key body motions. In regard to the latter, frames with the key body motions were identified for each participant for both design options and both environments, then the body motion data of these frames were assessed. To speed up the data post-processing, a structured Excel spreadsheet was created in which the 20 pre-selected relevant body joint angles were inserted as input to the automatic calculation of total REBA and RULA scores, the total risk level, and the sub-score risk of each body segment.

The videos generated automatically by the Xsens MVN Analyze 2020.0 software were used to conduct an analysis of the reachability of objects in the workstation. In the proposed method, reachability was evaluated with respect to maximum reach and thus accounted for the area covered by the arm when the entire arm was extended (Freivalds and Niebel 2009). Identifying motion patterns and subtasks in which participants were exposed to ergonomic risks in terms of reaching motions is essential to obtain significant results and formulating mathematical relationships between those risks and participants' body segments.

5.4.7. Assessment Comparison

In terms of the evaluation of design options, the REBA and RULA scores for different workstation design options were compared, and peak ratings and their frequency were identified for a continuous operation task. In addition, the average score was calculated, and the maximum and minimum were identified for each body segment score and for the total risk score. The data analysis involved the comparison of RULA and REBA sub-scores per body segment, total RULA and REBA scores, joint angles, maximum reach, and user perception. In order to compare the REBA and RULA scores, joint angles, and maximum reach obtained using the proposed method to those obtained using physical prototypes, the difference (D) and average error ($\overline{Error}$) were determine, as shown in Equations (6) and (7), where R_{PP} = risk score or joint angle obtained in the physical prototype; R_{VR} = risk score or joint angle obtained in the virtual reality; D_t = difference at a time t; and J = joint angle range for horizontal ($J = 180°$) and vertical ($J = 90°$) angles. In addition to the $\overline{Error}$, two other errors were calculated for the RULA and REBA scores: the global error (E_g) and the local error (E_l), as per Equations (8) and (9), respectively, where R_m = maximum total risk score. Negative values for D, E_g, and E_l indicate that the proposed method provided a more conservative ergonomic assessment than that provided by simulating the task using a physical prototype. As stated by Caputo et al. (2018b), this conservativeness can be an asset during the design phase of workstations. Lastly, to verify the body segments being mostly physically demanded, the normalized RULA and REBA sub-scores were calculated applying Equation (10), where R_e = sub-scores from the research experiment, and $R_{m,s}$ = maximum sub-scores of body segment.

$$Difference\ (D) = R_{PP} - R_{VR} \tag{6}$$

$$Average\ Error\ (\overline{Error}) = \sum_{i=1}^{n} \frac{D_t}{J} \tag{7}$$

$$Global\ error\ \left(E_g\right) = \frac{D}{R_m} \tag{8}$$

$$Local\ error\ (E_l) = \frac{D}{R_{PP}} \tag{9}$$

$$Normalized\ sub\text{-}rating = \frac{R_e}{R_{m,s}} \tag{10}$$

5.5. Feasibility Analysis

According to Seth et al. (2011), VR is ideal in terms of simulating assembly tasks because the tasks involve frequent and intuitive manual interactions. Thus, to demonstrate the proposed method, two design options were selected for a workstation at which hardware is installed on a window frame. As shown in Figure 5.4, these design options were proposed to replace an existing workstation in need of ergonomic improvements.

a. Current workstation in operation. b. Design A. c. Design B.

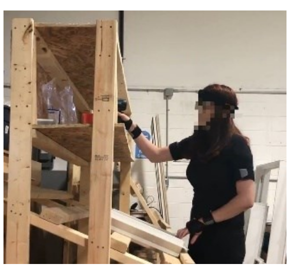
Figure 5.4: Current workstation design and designs options investigated in this study.

5.5.1. Identification of Key Design Parameters

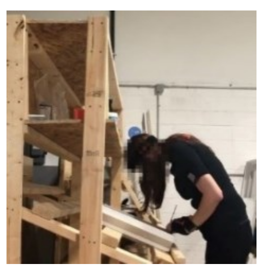
The primary differences between Design A and Design B were the angle of the work surface area (20° and 60°, respectively), and the height of the shelves where bins with hardware and tools were placed (approximately 135 cm and 122 cm in Design A and Design B, respectively). In this feasibility analysis, the key design parameters were the angle and the height of the work surface area, and the height of the shelves. However, it is worth noting that the work surface area had the same height, 85 cm, in both design options.

5.5.2. Identification of Key Body Motions

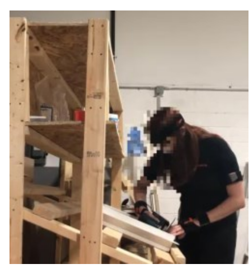
The task performed at this workstation was divided into two key body motions (KM1 and KM2). KM1 started from a free-standing posture followed by a motion of reaching forward with the arm to grasp a hardware component positioned on the shelf. Then, a move motion was performed to bring the hardware component to the window frame, initially positioned on the work surface area with its edge touching the edge of the workstation. KM1 was further divided into three therbligs: reach, move, and position. KM2, meanwhile, started immediately after KM1 was performed, and involves the motion of attaching the hardware to the window frame, corresponding to the assembly therblig. Both KM1 and KM2 were repeated three times per completed task. Accordingly, the body motion data of each participant was further segmented for ergonomic analysis purposes, resulting in 15 series of data for a continuous motion for each therblig and each prototyping environment. In Figure 5.5, demonstrations of these body motions in the physical prototype environment are provided.



a. KM1a: Reaching.



b. KM1b: Positioning.



c. KM2: Assembling.

Figure 5.5: Demonstrations of key motions performed in the physical prototype of Design A.

5.5.3. VR Model Design

The VR model designed for this feasibility analysis contained the two workstation designs under study represented at full scale as per the design specifications and in consideration of the identified key design parameters as shown in Figure 5.6. When participants engaged in the VR model, they were placed in a virtual off-site construction facility where they would see a window frame measuring 35 cm × 40 cm placed on the work surface of the workstation and hardware components representing the real-world ones were located in storage bins located on shelves as specified in the design drawings. A virtual hand was included in the VR environment to provide a better visualization of the commands trigged by the hand controller and participants were required to continue pressing the side buttons of the hand controller to hold a piece of equipment. The VR model was designed in such a manner that participants could interact with any hardware component or equipment located in the virtual workstation. It is worth mentioning that all equipment lifted in the VR environment weighs less than 2 kg.

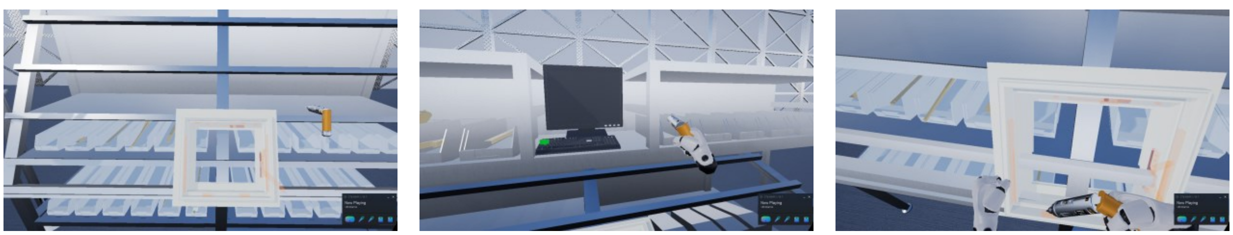


Figure 5.6: Views of the designed VR environment.

5.5.4. Data Acquisition

The data was acquired through a research experiment carried out with the same participants in two distinct facilities (*N*=5). First, participants completed the task in a research lab where the physical prototypes of the two proposed designs were assembled. Then, participants completed the task in the VR environment in a space with an unobstructed area measuring 1.80 m × 2.40 m, which encompassed a play area of 1.50 m × 2.10 m in the VR environment. Although participants needed a relatively small space to conduct the investigated task, a larger area was provided to guarantee participant safety while immersed in the VR environment. Although the analysis performed in this study did not consider intellectual skills such as learning and adaptation skills, the carryover effect was carefully considered in the experiment design. The physical and VR experiments were performed fourteen weeks apart to ensure that a participant's experience in one prototyping method did not have a significant impact on their performance in the other, thereby minimizing the carryover effect. The online questionnaire was sent to participants by email after they had completed both rounds of experiments.

5.5.4.1. Participants

To overcome the challenge of recruiting participants, particularly during a pandemic, participants with no history of musculoskeletal injuries were invited to voluntarily engage in this research experiment based on their physical stature to represent different percentiles of the North American population (Anderson 2016). This approach has been previously applied in a similar study (Peruzzini et al. 2019, 2020b), and it has been recommended in the literature as means of obtaining information about end-users during the work design phase (Freivalds and Niebel 2009). Three male participants (ID 1, 3, and 5) and two female participants (ID 2 and 4) ranging from 54 kg to 99 kg in body weight and from 26 to 31 years of age engaged in the experiment. Their height varied from 163 cm (ID 2 = 50th percentile among females) to 190 cm (ID 5 = 99th percentile among males). ID 1 corresponded to the 50th percentile among males, while ID 3 and ID 4 represented the 95th percentiles among males and females, respectively, based on height. Before participating in the experiment, participants were given information about this study and about the task to be performed, and were asked to sign a form consenting to participating in this research and appearing in photo and video data collected during the experiments. Then, 17 inertia sensors were placed on the participant's body segments. Each participant completed the continuous operational task once in each design option and once in each prototyping environment (i.e., VR and physical prototype).

5.5.5. Results and Discussion (Data Analysis)

5.5.5.1. RULA and REBA Total Risk Rating: Overall Continuous Operational Task

An ergonomic risk assessment of two design options was conducted based on body motion data obtained in the physical prototype (PP), benchmark for the conducted analysis, and in the VR environments. The interpretation of both the RULA and REBA scores calculated for the overall continuous operational task (Figure 5.7) indicated that both design options need further investigation to implement design changes to reduce ergonomic risks. (RULA scores ranging from 5 to 6 indicate that further investigation is needed, and changes should be done soon, while a RULA score of 7 indicates that changes should be implemented (McAtamney and Corlett 1993); REBA scores ranging from 4 to 7 indicates that the risk is medium and that the workstation design should change soon, while REBA scores ranging from 8 to 10 represent high risk and thus changes should be implemented (Hignett and McAtamney 2000).) As illustrated in Figure 5.7, participants spent slightly less time in a high-risk range in the Design B workstation, particularly taking into consideration RULA scores for the right side of the body (dominant side of all participants). Applying a criterion similar to that used by Li et al. (2018) to validate a framework to assess ergonomic risks through 3D modelling simulation, Table 5.2 details the RULA and REBA scores calculated for the continuous operational process. As noted, the maximum global error (E_g), error in relation to the maximum score of each risk assessment method, between the average ($\bar{x}$) risk score calculated in both environments was −8.29% (Participant ID 1) and 12.81% (Participant ID 5), for RULA and REBA, respectively, while the minimum E_g was found to be 0.29% (Participant ID 3) and −0.49% (Participant ID 3), with an $\bar{x}E_g$ of 3.48% and 4.17% for RULA and REBA, respectively. In this context, two conclusions can be drawn with respect to the E_g identified for both RULA and REBA: (1) the assessment of ergonomic risks applying the proposed method was more accurate when RULA was chosen as an assessment method, which indicates that the simulation of the upper body was more accurate in the VR environment, (2) although RULA and REBA have similarities in their criteria to evaluate ergonomic risks, the minor global error for each participant was not equivalent in both assessment methods. For instance, the E_g of Participant ID 3 was found to be 0.29% for RULA and 4.56% for REBA in Design A.

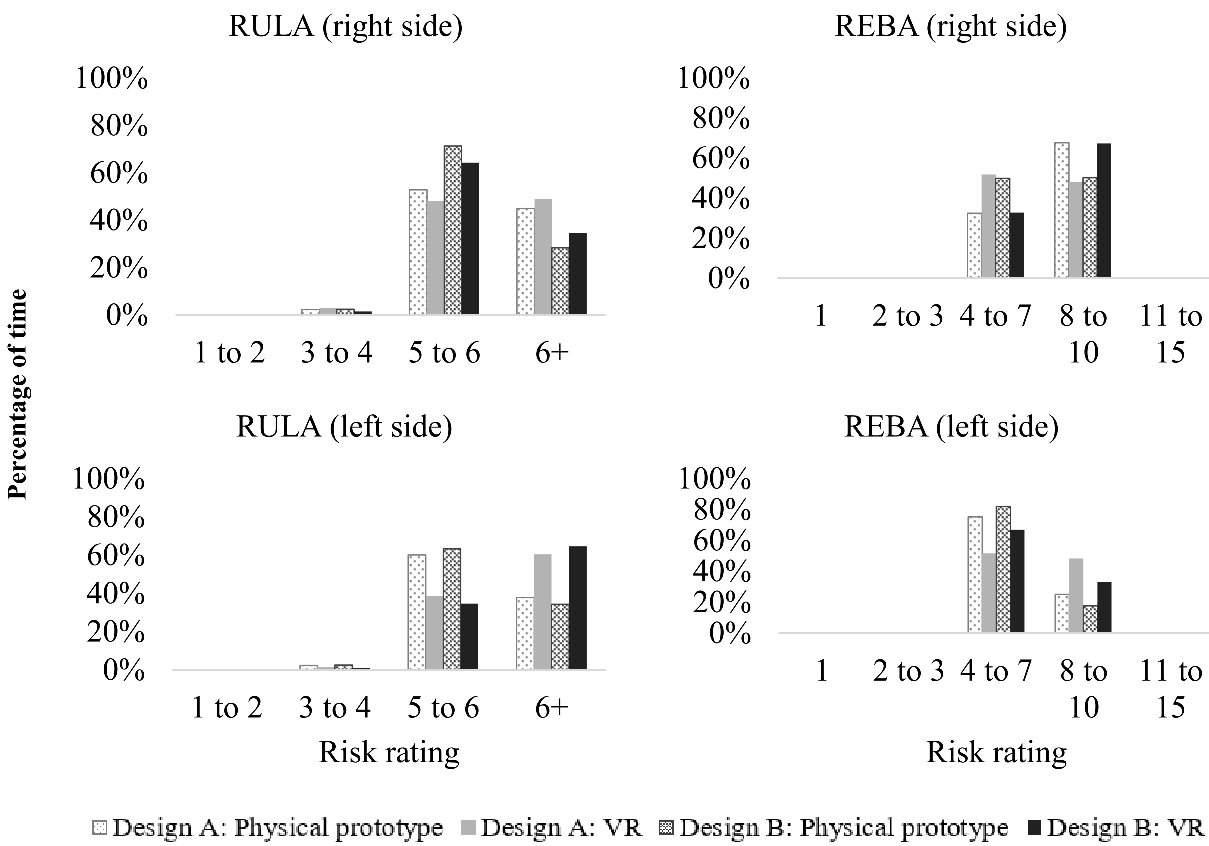


Figure 5.7: Percentage of median time spent at each risk range during the task in both environments.

Table 5.2: Total risk score comparison of all participants (right side, i.e., dominant side) in both design options.

	Risk assessment method	Factor	ID 1 VR	ID 1 PP	ID 2 VR	ID 2 PP	ID 3 VR	ID 3 PP	ID 4 VR	ID 4 PP	ID 5 VR	ID 5 PP
Design A	RULA	$\bar{x}$	6.52	6.16	6.51	6.48	6.45	6.47	5.98	6.22	6.02	6.36
		Max	7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00
		Min	4.00	3.00	3.00	4.00	4.00	4.00	3.00	3.00	4.00	3.00
		D	−0.37	—	−0.03	—	0.02	—	0.25	—	0.34	—
		E_g	−5.27%	—	−0.38%	—	0.29%	—	3.54%	—	4.88%	—
	REBA	$\bar{x}$	8.36	7.89	8.19	7.93	7.38	8.07	6.51	7.54	6.51	8.43
		Max	10.00	11.00	10.00	10.00	10.00	10.00	10.00	10.00	9.00	10.00
		Min	4.00	3.00	4.00	4.00	4.00	4.00	2.00	3.00	4.00	4.00
		D	−0.46	—	−0.26	—	0.68	—	1.03	—	1.92	—
		E_g	−3.09%	—	−1.74%	—	4.56%	—	6.89%	—	12.81%	—
Design B	RULA	$\bar{x}$	6.63	6.05	6.30	6.55	6.48	6.26	5.96	6.03	6.25	6.56
		Max	7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00
		Min	4.00	4.00	4.00	3.00	3.00	4.00	3.00	3.00	5.00	3.00

	D	−0.58	—	0.25	—	−0.22	—	0.07	—	0.31	—
	E_g	−8.29%	—	3.58%	—	−3.16%	—	0.97%	—	4.44%	—
	$\bar{x}$	8.24	7.45	8.03	8.16	7.38	7.31	6.65	6.38	7.75	8.37
	Max	10.00	10.00	10.00	10.00	10.00	9.00	10.00	9.00	10.00	10.00
REBA	*Min*	4.00	3.00	4.00	2.00	3.00	4.00	3.00	4.00	4.00	4.00
	D	−0.79	—	0.13	—	−0.07	—	−0.27	—	0.62	—
	E_g	−5.26%	—	0.89%	—	−0.49%	—	−1.80%	—	4.14%	—

Note: Abbreviations used in the table: *Max* = maximum score | *Min* = minimum score.

Another critical factor to be compared between the different assessment methods is the maximum (*Max*) score obtained in each environment because it indicates the peak physical demand associated with exposure to a high-risk range. The proposed method yielded an accurate identification of maximum risks using RULA as an assessment method (Table 5.2) which allows a proactive identification of these risks using the proposed method. It is worth noting that few (N = 4 out of 10) REBA maximum scores differed by 1, which, in most cases (N = 3), yielded the same risk level; however, this difference resulted in a different interpretation of risk level for Participant ID 1. This finding also suggests that the proposed method is more accurate when used to assess ergonomic risks in the context of applying RULA.

Furthermore, with respect to Figure 5.7, it was observed that the risk rating calculated for the participants' dominant side had a higher degree of similarity between the physical prototype and the VR; this finding was attributed to the fact that the VR environment was designed focusing on the primary motions required to finalize the task and most of these motions were performed with the participant's dominant hand. The total RULA scores indicated that both right and left sides of the body were subjected to similar ergonomic risks, whereas the REBA scores indicated that the right side was most physically demanded (Figure 5.7), which is aligned with the fact that all participants are right-handed. It was also observed that the ergonomic risks calculated in the VR environment using RULA were higher (i.e., more time was spent in a high-risk range) than those calculated in the physical prototype, which suggests that the VR environment results in a more conservative ergonomic risk assessment.

5.5.5.2. RULA and REBA Total Risk Rating: Key Body Motions

According to RULA and REBA, participants were exposed to the medium-risk category ($\bar{x}$RULA = 6; $\bar{x}$REBA = 7) during KM1, which included the therbligs of reaching, moving, and positioning; and the high-risk category ($\bar{x}$RULA = 7; $\bar{x}$REBA = 8) during KM2, which accounted for the assembly therblig. The total RULA and REBA scores per side of the body, environment, and design option of the identified key motions are depicted in Figure 5.8. A consistency was observed between the total risk score calculated from the VR and the physical prototype for the right side of the body in KM1, while a slight inconsistency was found for the left side of the body. For instance, the $\bar{x}$RULA score calculated by applying the proposed method surpassed that of the physical prototype by 1 in Design B, indicating a more conservative estimation of ergonomic risks in the VR environment. In terms of KM2, a consistency was observed between RULA scores calculated for both sides of the body and prototyping environments, except for the $\bar{x}$RULA score calculated for the right side of the body in Design B in which the $\bar{x}$RULA score obtained with the physical prototype and the VR environment differed by 1. Despite having a higher variation in the total risk score between participants and environments, the $\bar{x}$REBA total risk score calculated for KM2 falls in the "high" risk category in both design options and for both prototyping methods. Aligned with the findings for the overall continuous operational task, RULA assessment yielded more precise estimation of ergonomic risks in the VR environment, particularly for the dominant side of the body (i.e., right side). The average local error (E_l), which corresponds to the error between the total risk score obtained with the proposed method in comparison to that of the benchmark, for KM1 for the right side of the body was found to approximately 3% for RULA in both design options, and approximately 10% and 5% for REBA in Design A and Design B, respectively. For KM2, $\bar{x}E_l$ was determined to approximately 6% and 8% for RULA, and 10% and 20% for REBA in Design

A and Design B, respectively. The $\bar{x}E_g$ for the right side of the body was approximately 2% and 3% for RULA, and 5% and 2% for REBA for KM1 in Design A and Design B, respectively; while for KM2, an $\bar{x}E_g$ of approximately 5% and 8% for RULA, and 14% and 9% for REBA in Design A and Design B, respectively. Based on these findings, it was determined that the proposed method provided more accurate estimation of motions included in KM1 (i.e., reaching, moving, and positioning therbligs) compared to KM2.

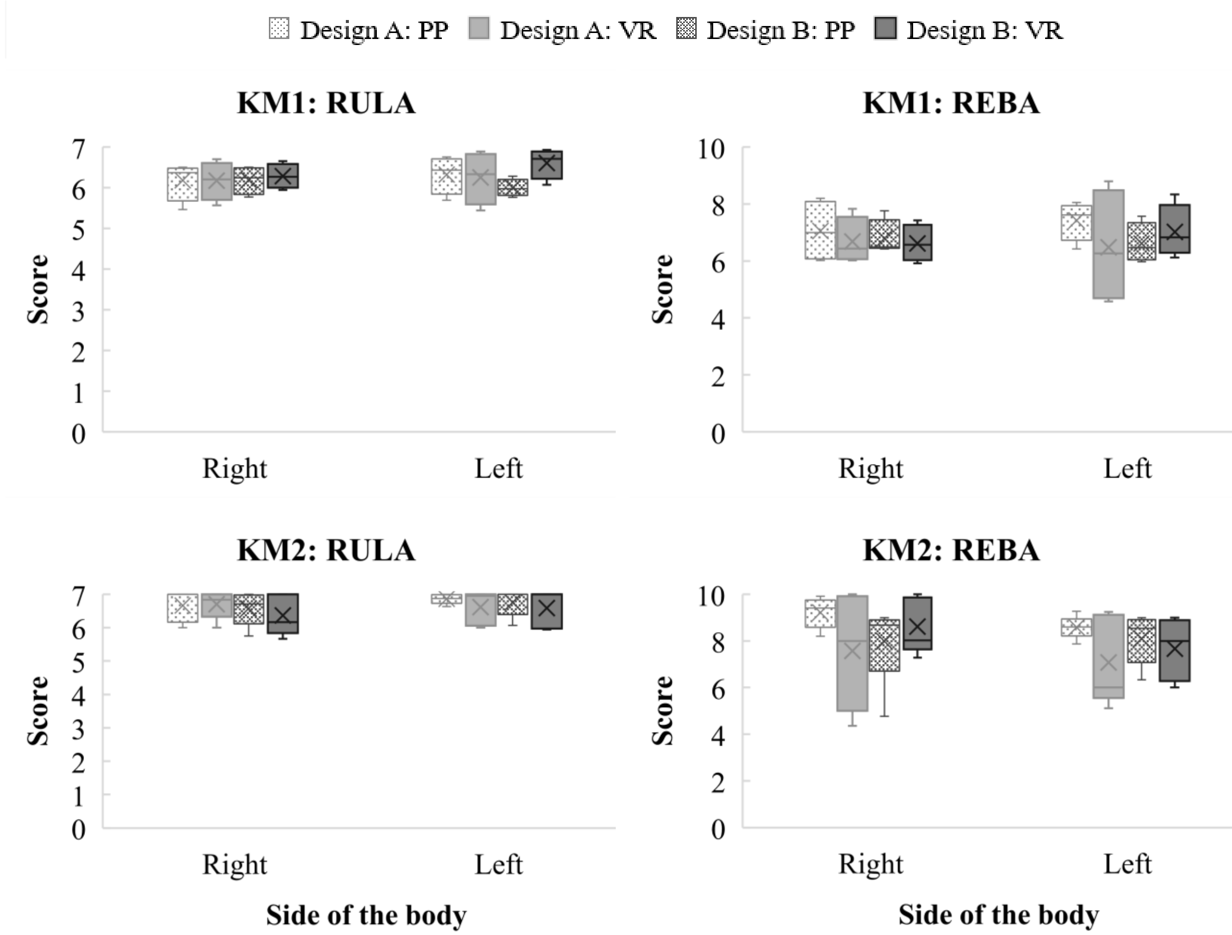


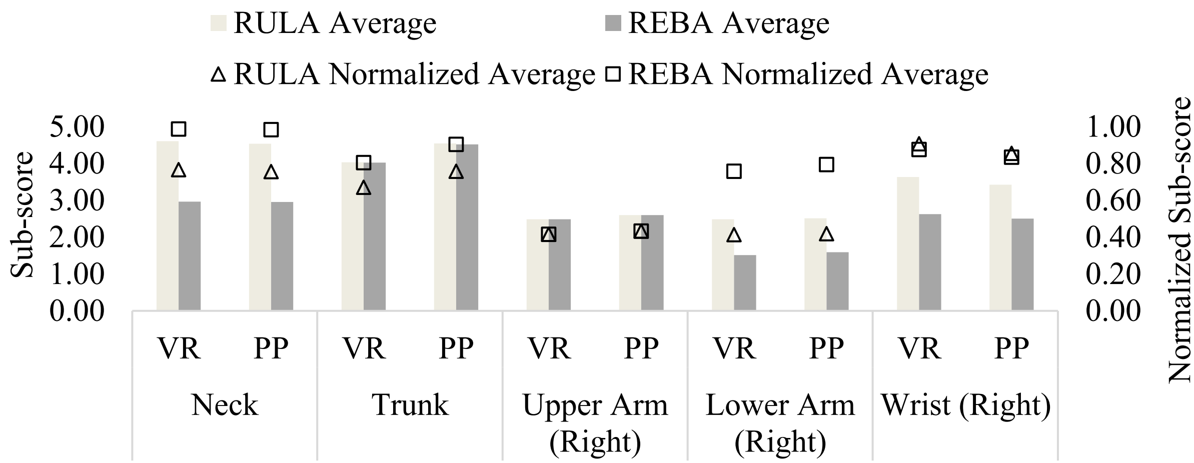
Figure 5.8: Total RULA and REBA scores per key motions for both design options and environments.

The Pearson's correlation coefficient (ρ) was calculated for the therbligs of reach, move, position, and assembly. The interpretation of the ρ coefficient is as follows: $\rho \leq 0.35$ = weak correlation, $0.36 \leq \rho \leq 0.67$ = moderate correlation, $0.68 \leq \rho \leq 0.89$ = high correlation, and $\rho \geq 0.90$ = very high correlation (Taylor 1990). The calculation of ρ takes into account that the therbligs were repeated in both design options (N = 15 per prototyping environment). Based on RULA, the results demonstrated that the risk assessment performed using the proposed method successfully simulated reaching and positioning therbligs (ρ = 0.80 and 0.94, respectively), which were motions frequently repeated at the workstation under investigation. A fairly good linear correlation was found between RULA scores calculated for both environments for the move therblig (ρ = 0.71). On the other hand, a weak linear correlation was identified for the assembly therblig (ρ = 0.17 and 0.32 for RULA and REBA, respectively). The correlation of REBA scores was also analyzed for the same therbligs; ρ was found to equal 0.76, 0.58, and 0.75 for the reach, move, and position therblig, respectively. In light of these findings, two conclusions can be drawn: (1) RULA assessment yielded stronger correlation than REBA when simulating overall continuous operational task in the VR environment for ergonomic evaluation purposes, (2) the VR accurately simulated the physical interactions with the workstation such that the assessment of ergonomic risks associated with reaching and positioning therbligs could be accurately performed using the proposed method.

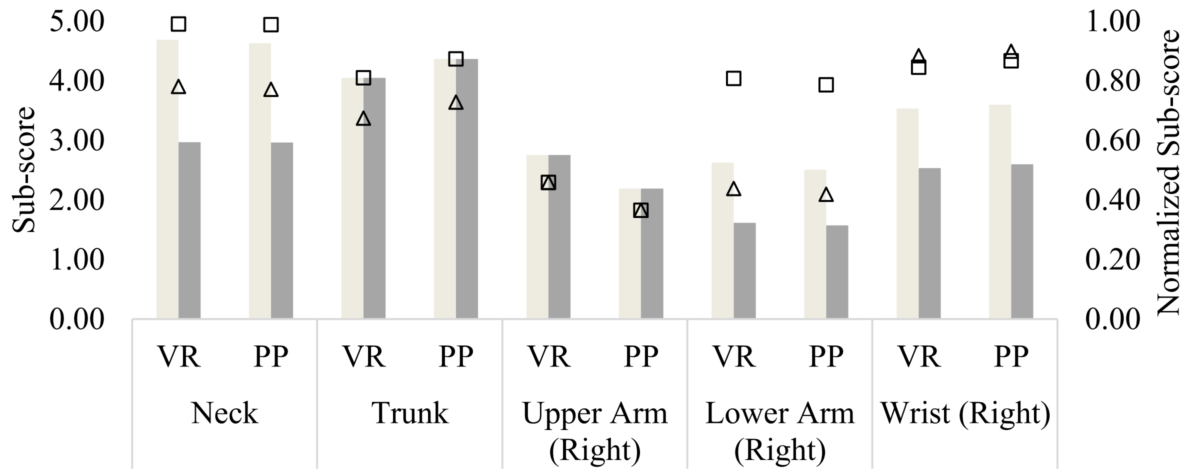
5.5.5.3. RULA and REBA Sub-scores per Body Segment: Overall Continuous Operational Task

The average sub-score of body segments considering the practical application as an overall continuous operational task indicated that the proposed VR–MOCAP method results in accurate simulation of neck, lower arms, and wrists motions since the difference of their sub-scores obtained from the proposed method and the physical prototype is lesser than 0.10. On the other hand, prediction of trunk average sub-score was slightly less accurate ($\pm 0.25 < D < \pm 0.50$); while upper arm sub-scores were somewhat accurate with a difference lower than 0.25. Features to ensure that the window frame touches the work surface area during most of subtasks, excepting when the window frame is being rotated, are recommended to be incorporated to the VR application of future studies to increase the similarities between the VR and the physical prototype. This improvement to the VR application has an impact on the joint angles of trunk and upper arms, thus altering their respective sub-score.

In regard to physical demands on body segments, Figure 5.9 contains the average sub-score (i.e., the sub-score calculated combining the vertical and horizontal angles) obtained for each body segment and the normalized RULA and REBA scores calculated for each environment for the overall continuous operational task. (For conciseness, only the right-side of the body is shown as all participants were right-handed, and thus, the right side of the body was subject to a higher degree of physical demand). Although the task required participants to lift their upper arm to reach the shelves where the hardware components were stored, participants' upper arms were scored in the mid-risk range. Additionally, the exposure to risk was significantly higher on participants' right wrists according to the normalized average RULA and REBA sub-scores. According to REBA and RULA assessments, neck, trunk, and right lower arm also scored in the high-risk range. In terms of the normalized average REBA sub-scores for participants' necks, they were remarkably close to 1 in both design options, which indicates that this body segment was frequently exposed to an ergonomic risk in the highest-risk range category during the completion of the task. These findings revealed that the investigated design options need further investigation to reduce the physical demands imposed on participants' wrists, necks, trunks, and lower arms. In addition, Figure 5.9 also shows the similarity between the average RULA and REBA body segment sub-scores for the overall continuous operational task that were obtained using the proposed method and using the physical prototype.



a. Average risk sub-score per body segment of all participants for the continuous operation—Design A.



b. Average risk sub-score per body segment of all participants for the continuous operation—Design B.

Figure 5.9: Average of all participants' risk sub-scores per body segment for both design options and both environments.

5.5.5.4. RULA and REBA Sub-scores per Body Segment: Key Motions

As all participants are right-handed, this side of the body was analyzed in detail and the findings are described in this subsection. It was observed that the VR successfully simulated, with a $\bar{x}E_l$

below 12%, the motions pertaining to the trunk for KM1 and KM2 based on both RULA and REBA assessments. As evidenced in Figure 5.10, errors between the RULA sub-score obtained from the VR environment and the physical prototype yielded a maximum $\bar{x}E_g$ of −13% found in the neck in KM1, and a minimum $\bar{x}E_g$ of ±1% accounted for both the neck and wrist in KM1. For REBA, the maximum $\bar{x}E_g$ was found to equal 10% for the neck in KM2 and the minimum was 0% for the neck in KM1. In this context, a greater difference between the sub-scores of KM2 and KM1 was observed. An explanation for this finding may be the fact that in the physical prototype the motions as defined by KM2 were performed with the window frame leaning on the workstation, while this was not always the case in the VR environment due to the absence of window's weight. Features to ensure that the object being handled is touching the work surface area are recommended for other studies in this area.

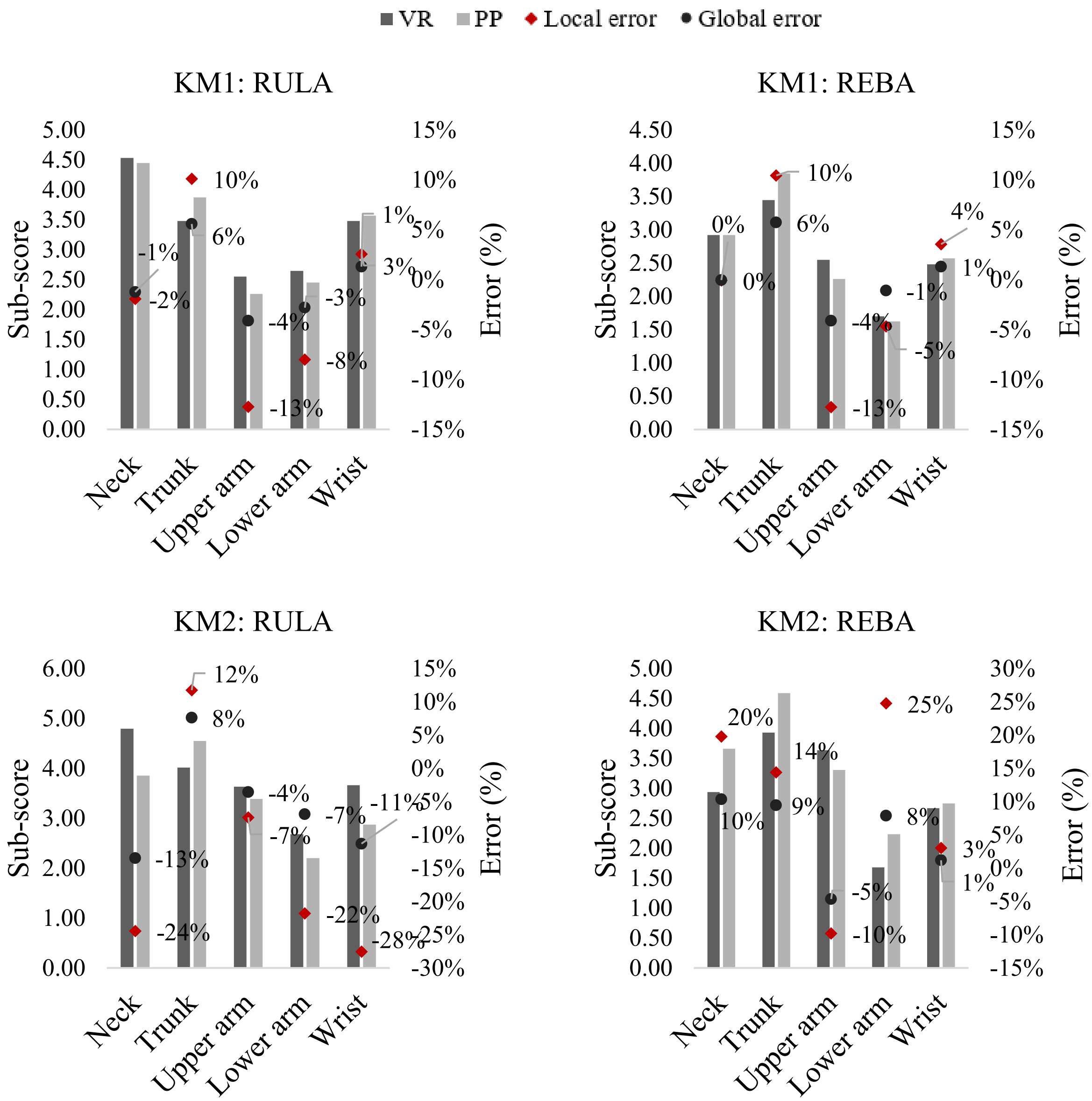


Figure 5.10: Sub-scores per body segment for all participants for the key motions.

Using the reach therblig as an example ($N = 15$ per prototyping environment), the analysis of the sub-scores per body segment, the distribution of sub-scores per body segment, and the total risk score in both design options and environments are presented in Figure 5.11. The reach therblig was chosen as it is frequently repeated in the workstation under investigation and its motion is a function of the workstation design (i.e., the height of the shelf has an impact on the horizontal and vertical distances being reached by participants). According to RULA and REBA assessments, the reach therblig falls in the “medium” risk category in both design options for the dominant side of the body. As shown in Figure 5.11, the trunk was the body segment with highest correlation between the RULA and REBA sub-scores obtained from the VR and the physical prototype, ρ = 0.76. A fairly good correlation was also found for the neck sub-scores in the context of applying RULA and REBA; ρ = 0.70 and 0.75, respectively. For RULA and REBA, the $\bar{x}E_g$ for the trunk was found to be approximately 3%, while an $\bar{x}E_g$ of 8.64% and 4.35% was calculated for the neck considering RULA and REBA, respectively. This higher $\bar{x}E_g$ for the RULA sub-score of the neck was because RULA attributes a sub-score for the neck’s position based on four ranges of joint angles (0°–10° = 1; 10°–20° = 2; above 20° = 3, and below 0° = 4); in contrast, REBA has only two ranges of joint angles (0°–20° = 1; and above 20° or below 0° = 2). In both RULA and REBA, the sub-score from the VR environment was higher than that from the physical prototyping suggesting that the VR provides a more conservative estimation of ergonomic risks associated with the neck. For RULA and REBA assessments of the reaching motion, the body segments with the greater discrepancies between the sub-score from the VR and from the physical prototype were the lower arm and the wrist. Despite this increased error in the sub-score for these body segments, their risk scores stayed within the same integer value for the REBA sub-score.

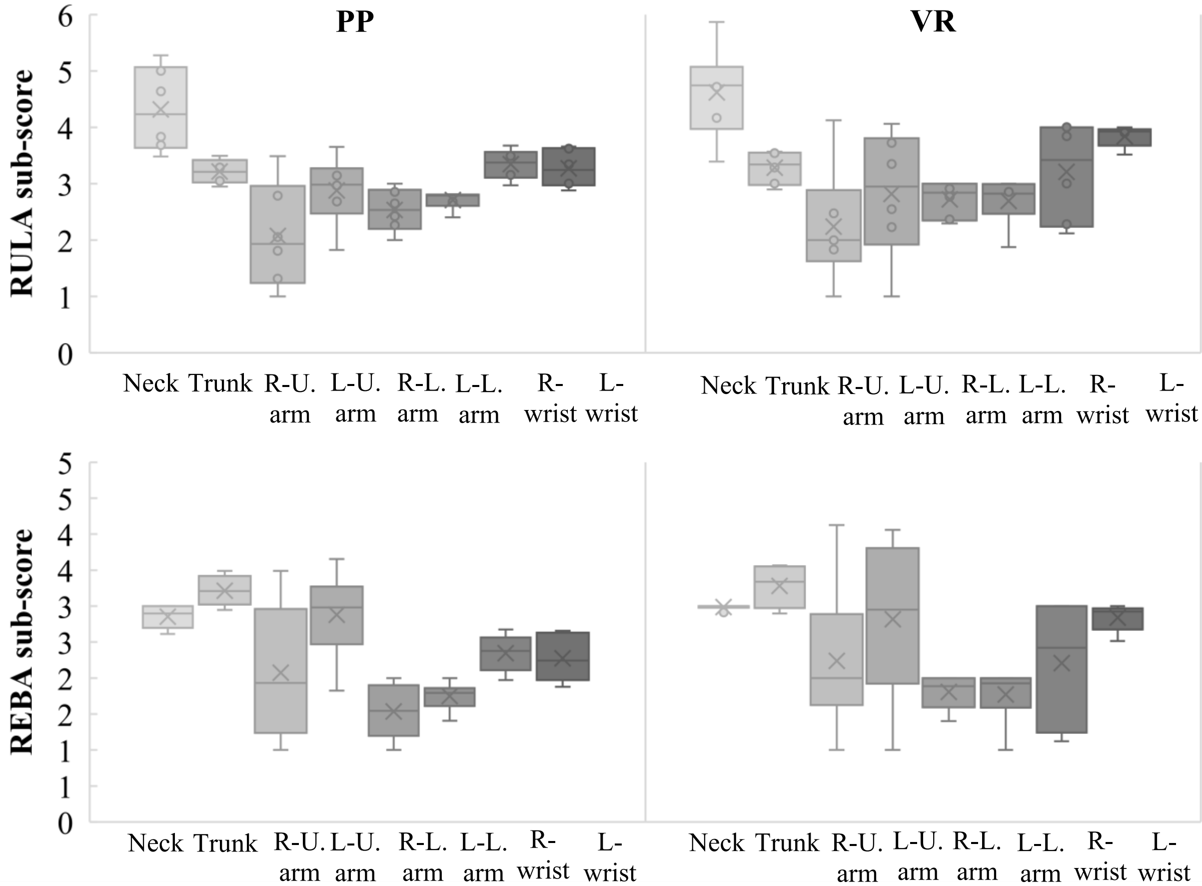


Figure 5.11: Sub-scores per body segment for all participants for the key motions.

5.5.5.5. Joint Angles

For the comparison of joint angles, the defined key motions were used to ensure that similar motions were being performed in both environments, and the data collected from the research experiment were randomly trimmed to avoid bias so the total time frame of a participant in one environment matched that of the same participant in the other environment. The results for KM1 and KM2 indicated that among the flexion angles of the body segments relevant to both RULA and REBA (10 flexion angles per 5 participants and 2 primary motions), 91% and 89% of the joint angles obtained an error within ±20% in Designs A and B, respectively. Most of the joint angles with an error greater than ±20% were found in KM2 in Design B. It was thus observed that the simulation of motions similar to those of KM1 (i.e., reaching to pick hardware from a shelf and placing it on the window frame) were performed successfully using VR. In contrast, motions presented in KM2 (i.e., attaching hardware to the window frame) required further investigation to increase their accuracy, particularly in terms of wrists, right upper arm, and neck. With respect to error per participant, it was noted that Participant ID 5 accounted for 50% of the error above ±20% in both Designs A and B. Moreover, the joint angles of Participants ID 3 and 4 were the most accurately represented among all participants each accounting for 6% of errors above ±20% in both design options. To determine whether the accuracy of the motions performed in the VR environment had a strong correlation to the stature of the subject/participant, an increase in the number of participants is suggested in future research studies. Using Participant ID 3 and the primary body posture KM2 in Design A as an example in Figure 5.12, the joint angles from both methods show a comparable trend, which indicates that similar motions were performed in both the VR and physical prototype environments. However, discrepancies between the joint angles of both environments were verified. Nonetheless, these gaps did not have a significant impact on the assessment of ergonomic risks since both RULA and REBA attribute a similar sub-score for a joint angle range. As detailed in Figure 5.12, the $\overline{Error}$ varied from 1% (left lower arm) to 15% (right upper arm).

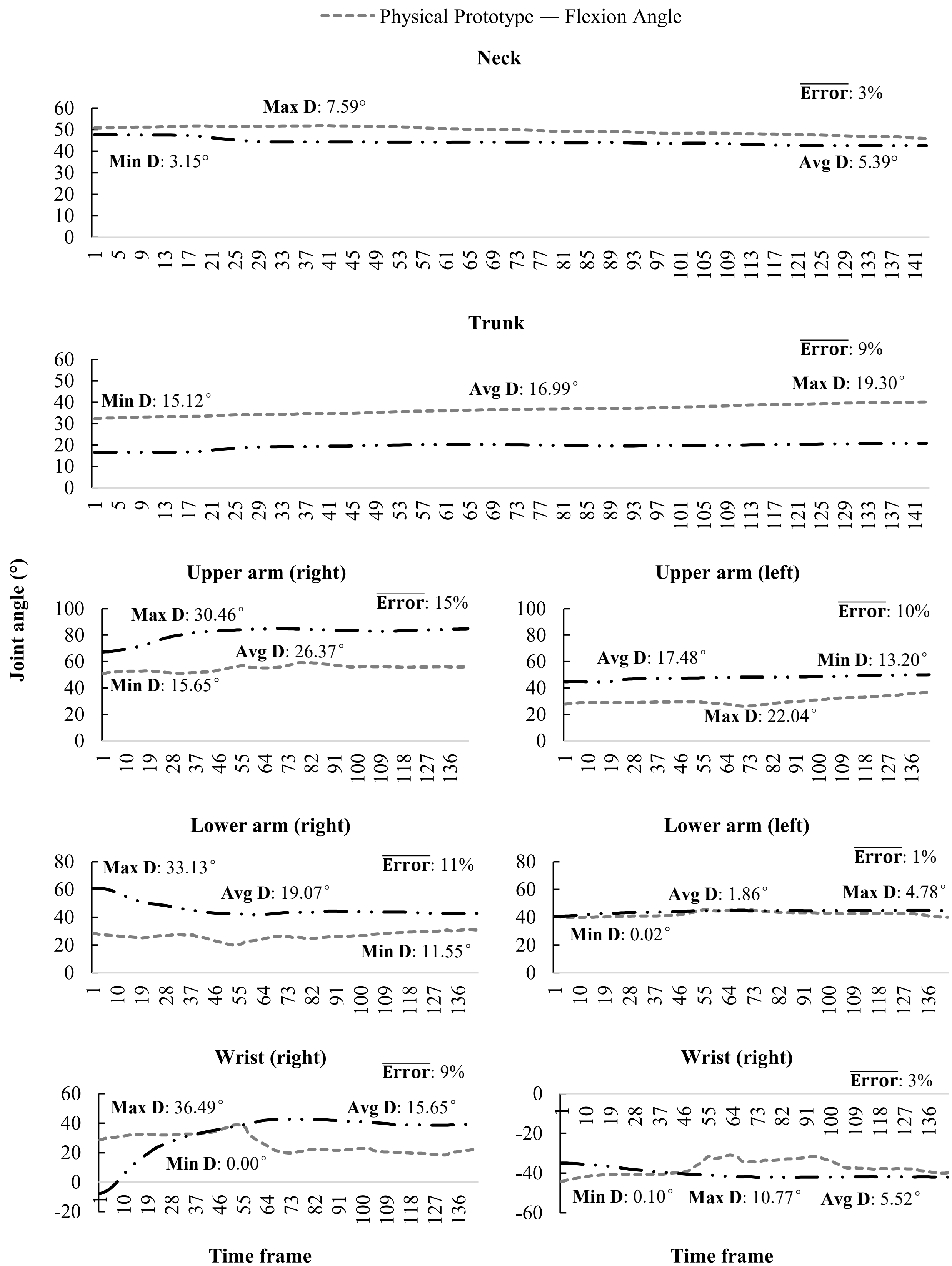

Physical Prototype — Flexion Angle
Neck
Error: 3%
Max D: 7.59°
Min D: 3.15°
Avg D: 5.39°
Trunk
Error: 9%
Min D: 15.12°
Avg D: 16.99°
Max D: 19.30°
Joint angle (°)
Upper arm (right)
Max D: 30.46°
Error: 15%
Avg D: 26.37°
Min D: 15.65°
Upper arm (left)
Error: 10%
Avg D: 17.48°
Min D: 13.20°
Max D: 22.04°
Lower arm (right)
Max D: 33.13°
Error: 11%
Avg D: 19.07°
Min D: 11.55°
Lower arm (left)
Error: 1%
Avg D: 1.86°
Max D: 4.78°
Min D: 0.02°
Wrist (right)
Error: 9%
Max D: 36.49°
Avg D: 15.65°
Min D: 0.00°
Wrist (right)
Error: 3%
Min D: 0.10°
Max D: 10.77°
Avg D: 5.52°
Time frame
Time frame

Figure 5.12: Joint angle comparisons of body segments (Participant ID 3 — KM2 in Design A).

5.5.5.6. Reachability analysis of hardware and equipment

Based on the findings obtained, it was identified that Participants ID 1, 2, and 4, faced reachability issues in both the VR and the physical prototypes of Design A and B; while Participants ID 3 and 5 (second highest and highest stature among all participants) were able to complete the task without adding physical demands to their body due to reaching motions. Among all participants, Participant ID 2 was exposed to more physically demanding reaching motions as a result of her stature (lowest stature among all participants). The reachability issues found in the feasibility analysis of the proposed method were divided into two categories: (a) front-oriented reaching when participants need to grasp an element located further away from the edge of the shelf; (b) side-oriented reaching to grasp either the compact drill driver located on the right-side of the shelf or the hinge located in a bin on the far-left-side of the shelf. The results demonstrated that these categories followed a pattern from which a mathematical relationship was formulated as expressed in Equation (11), in which η, α, and δ account for the flexion angle of the neck, upper arm, and lower arm, respectively. Furthermore, it was determined that the reaching motions described by Equation (11) yielded a total RULA score of 7 and a total REBA score varying from 8 to 10 for both design options and environments for all participants. This indicated that these reachability issues were responsible for exposing participants to the highest-risk category in the context of applying RULA and the second highest-risk category based on REBA. Therefore, adjustments need to be made to the height of the shelf while the workstation is being designed to eliminate the exposure of workers to those risks. Similarly to the RULA and REBA assessments, the VR environment produced a more conservative reachability analysis since participants spent more time within the limits of Equation (11) in the virtual environment. Although participants were exposed to similar risk categories in both design options, they spent more time facing reaching issues in Design B, both in the physical prototype and the proposed method.

If: (11)

$\eta < 0°$;

$45° \leq \alpha \leq 180°$;

$\delta \ \leq 50°$; and

Upper arm is abducted or should is raised

$\Rightarrow Reachability\ issue$

$\Rightarrow$ *RULA score* $= 7$ $(highest\ risk\ category)$; $8\ \leq$ *REBA score* ≤ 10 *(second highest risk category)*

5.5.5.7. Questionnaire Results

The responses to the questionnaire indicated that participants perceived the task as having low mental demands and high physical demands and as eliciting a very low frustration level and a feeling of having accomplished it with high level of performance (Figure 5.13). In addition, the questionnaire responses demonstrated neutrality in terms of the task's time and effort demands. The participants did not feel that the task had a fast pace because a time by which the task must be finalized was not provided to them and they only had to complete the task once in each design option and prototyping environment. This would not be the case for a workstation in operation in an off-site construction facility. In terms of the designed VR models, participants strongly agreed that they felt safe and immersed in the VR environment as well as that they had a good understanding of the task and that they could see all the pieces of equipment required to complete it as shown in Figure 5.14. Participants agreed that the VR models were intuitive and provided a close representation of reality with similarities with the real-world task. Lastly, they agreed that they could pick up virtual tools and equipment easily and that they felt their body motions were similar in both prototyping environments.

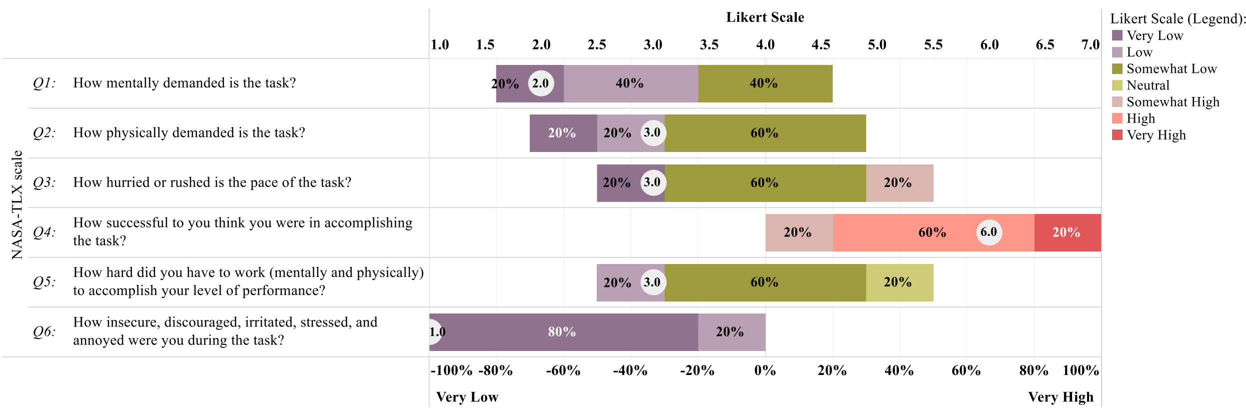


Figure 5.13: Questionnaire responses to NASA-LTX method.

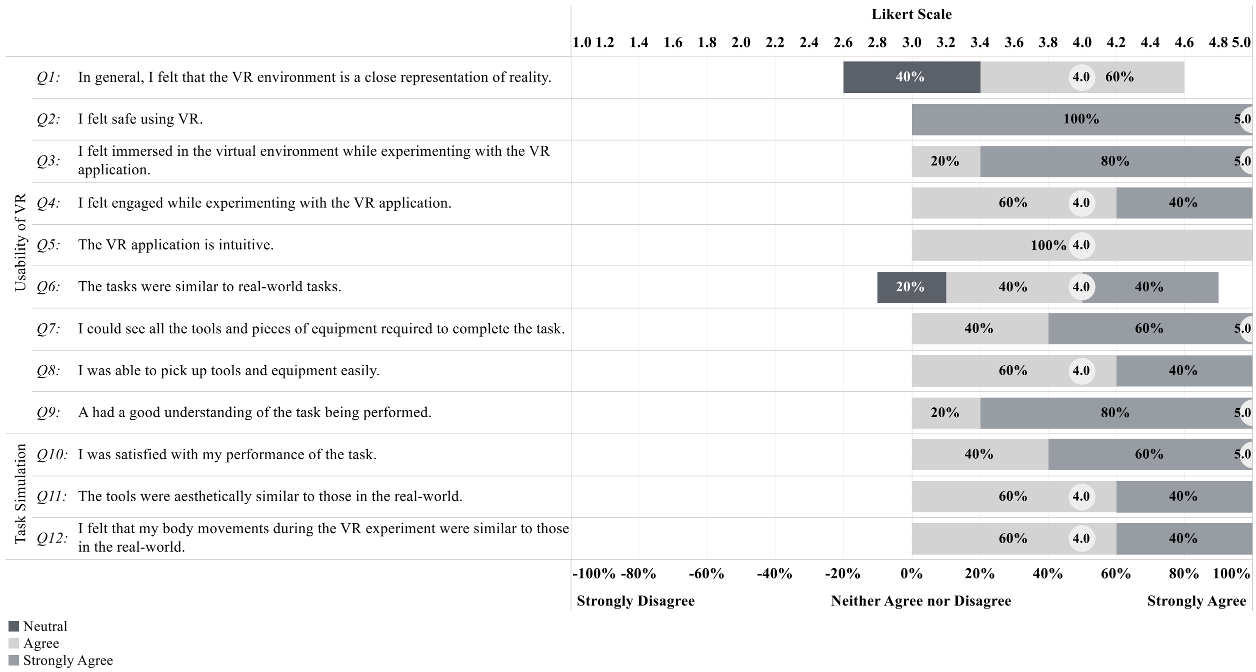


Figure 5.14: Questionnaire responses in terms of usability of VR and task simulation.

5.6. Limitations and Future Work

Overall, the proposed method results in a more conservative ergonomic risk assessment, as participants spent more time in a high-risk category in the VR environment, which is aligned with the results obtained by Caputo et al. (2018b) while evaluating EAWS index in a VR environment. However, it should be noted that the trunk flexion angles were lower in the VR environment than in the physical prototype environment due to the holding of the virtual window frame from the virtual workstation while attaching the hardware to the window frame, which was a motion not encountered in the physical prototype during the same subtask. This is evidenced by the greater difference between the trunk and neck sub-scores in KM2 in the VR environment as compared to the physical prototype environment, as per Figure 5.10. To overcome this limitation and increase the accuracy of trunk and neck sub-scores, a feature in the VR environment can be added to ensure that the window frame is touching the workstation such that it is held in place when participants are placing and attaching the hardware to the window frame. Although this study evaluated perceived mental and physical workload using a questionnaire, further investigation is required to assess cognitive and emotional human psychophysical measurements. Since the completion of the task was not time sensitive, participants did not feel pressure to complete the task at a fast pace. This limitation will be addressed in future studies by setting a maximum duration to finalize the task based on time studies or feedback from key personnel from off-site construction facilities.

While the size of the sample of participants is in line with previous studies in this area (Li et al. 2018; Peruzzini et al. 2019, 2020b; Vignais et al. 2013; Wang et al. 2021), it still imposes a limitation in terms of the statistical power of the analysis of the results obtained due to the limited size of the dataset. Despite this limitation, the sample size of participants was sufficient to demonstrate the feasibility of a practical application of the proposed method. A similar approach was applied in a recent study by Peruzzini et al. (2020b) validating a proposed ergonomic evaluation framework. Nonetheless, the number of participants will be expanded in future studies as part of a robust validation of the proposed method.

To address the abovementioned limitations and expand the research in this area, the future work direction is to (1) evaluate the impact of workstation design modifications on ergonomic risks virtually thus reducing costs associated with physical prototypes; (2) provide ergonomic feedback during the simulation of tasks in the off-site construction industry to identify and prevent worker behaviours that increase ergonomic risks; (3) expand the recruitment of participants to provide a robust statistical validation of the proposed method; (4) investigate whether participants stature is related to the accuracy of the motions in the VR environment; and (5) conduct research experiments using other experimental design methods.

5.7. Conclusion

This study proposes the use of VR technology and a MOCAP system to simulate and analyze human body motions for workstation design, as well as for ascertaining participants' perception of the physical and tasks being performed (acquired through a questionnaire). Accordingly, this research addresses the research problems identified in the existing literature and contributes to the body of knowledge and the off-site construction industry by providing a VR–MOCAP-enabled ergonomic risk assessment method that can be employed in a laboratory setting to mimic and anticipate what body motions are required in the performance of a given task such that ergonomic risks can be identified and mitigated in off-site construction early in the workstation stage. The proposed VR–MOCAP-enabled ergonomic risk assessment method provides holistic ergonomic analysis that combines objective and subjective criteria. As such, the need for physical prototypes is reduced through the simulation of real-world tasks in a virtual and immersive environment, thereby reducing the cost and time required to modify a workstation design and implement the improved design on the production line. A feasibility analysis of the proposed VR–MOCAP-enabled ergonomic risk assessment method is presented to demonstrate the feasibility of implementing the proposed method. In this feasibility analysis, participants completed the same task in both a physical prototype and a VR environment. Both RULA and REBA methods were applied to assess the ergonomic risks of two design options that were proposed as a substitute for an existing workstation in which hardware is installed to a window frame. Based on the results obtained, it is observed that the proposed method yielded more accurate results when RULA was used as the assessment method. It was also observed that the ergonomic risks calculated for the VR environment were higher (i.e., more time spent in a higher risk rating) than those calculated for the physical prototype, which indicates that the VR environment results in a more conservative ergonomic risk assessment. The comparison between the RULA and REBA total risk ratings calculated for an overall continuous operational task indicates that the proposed method is able to simulate human body motions in a laboratory setting for ergonomic purposes since the maximum global error, error in relation to the maximum score of each risk assessment method, is found to be −8.29% and 12.81% for RULA and REBA, respectively.

5.8. Data Availability Statement

Some or all data (anonymized data collected during research experiments), models (VR models), or code that support the findings of this study are available from the corresponding author upon reasonable request.

5.9. Acknowledgments

The authors appreciate the technical writing assistance of Kristin Berg. The authors also express their gratitude to Melissa McNeil for assisting in designing the 3D scenes used in the VR model, to Mohammad Darwish, Ammar Muhrez, and Anas Itani for assembling the physical prototypes, to Anas Itani for providing the design options evaluated in this study, and to all the volunteers that participated in the experiment. The authors also acknowledge the support from their industry partner, All Weather Windows. This work was supported by the University of Alberta and the Natural Sciences and Engineering Research Council of Canada (NSERC) Discovery Grant [grant number RGPIN-2019-04585] and Collaborative Research and Development Grant [grant number CRDPJ 533884-18].

CHAPTER 6: A VIRTUAL REALITY APPROACH COMBINING REAL-TIME ERGONOMIC ASSESSMENT WITH POSTURAL RECOMMENDATIONS DURING TRAINING ON INDUSTRIALIZED CONSTRUCTION TASKS[4]

6.1. Introduction

In industrialized construction facilities, products and processes are standardized to increase productivity (Bertelsen 2004). In this scenario, most construction tasks are carried out in automated or semi-automated workstations. Nevertheless, workers are still exposed to ergonomic risks in these facilities due to deficiencies in the workstation design and the requirement to undertake work of a highly physically demanding nature, often including forceful exertion, awkward body postures, and repetitive motion (Golabchi et al. 2016; Liu et al. 2019) that can cause fatigue (Umer et al. 2020) and work-related musculoskeletal disorders (WMSDs) (Canadian Centre for Occupational Health and Safety 2017). Both fatigue and WMSDs decrease workers' productivity, motivation, and physical and cognitive abilities, making them more prone to committing mistakes that may result in accidents (Aryal et al. 2017; Gatti et al. 2014b) In addition, WMSDs are correlated with high absenteeism, increased workers' compensation costs, and early retirement, thus resulting in social and financial losses (Botti et al. 2017; Inyang and Al-Hussein 2011). Workers' behaviour also plays an essential role in determining their exposure to risks, since unsafe behaviour is the most frequent cause of construction injuries (Li et al. 2015b). One of the key determinants of workers' behaviour is their ability to identify and evaluate risks, and this is

[4] The manuscript appearing as Chapter 6 of this thesis is under review for publication in *Automation in Construction* as of the time of writing of this thesis.

acquired through experience and training (Sacks et al. 2013). Assessing the ergonomic risks at a workstation and providing preventive measures such as ergonomics training to workers is thus necessary not only to support a safer workplace and reduce long-term exposure of workers to ergonomic risks associated with fatigue and WMSDs, but also to improve productivity.

Ergonomics training focuses on educating workers to identify the risk factors responsible for WMSDs, to adjust the workstation for their needs, and to select the appropriate equipment and use it properly (Hoe et al. 2012). Yan et al. (Yan et al. 2017) state that workers can be made aware of ergonomically hazardous postures inherent in specific tasks through adequate training that incorporates real-time ergonomic assessment. This, in turn, supports behavioural adjustments to reduce long-term exposure to these postures. In this respect, Vignais et al. (Vignais et al. 2013) indicate that a real-time ergonomic system for training purposes is needed. On the other hand, Faisting and Sato (Faisting and Sato 2019) conclude, based on a review of the literature in this area, that there is no consistent evidence of the beneficial impacts of ergonomics training in reducing physical demand or the risk of developing a WMSD, underscoring the research opportunities in this area.

Traditionally, training in this area has typically been in the form of lectures, videos, and on-site training sessions (Schwarze et al. 2019). As such, the acquisition of real-time body motion data by which to assess ergonomic risks is commonly done during the on-site training, resulting in disruptions to the production line, productivity loss, and trainee exposure to actual ergonomic risks during training (Li et al. 2015a). The use of Kinect cameras (Ray and Teizer 2012), mockup workstations (Sigurdsson et al. 2011), and virtual reality (VR) (Barkokebas et al. 2019; Dias Barkokebas and Li 2021) in laboratory settings and the use of augmented reality (Placencio-

Hidalgo et al. 2022) on site have been explored as possible solutions to address the limitation mentioned above with respect to acquiring data during on-site training. VR in particular is as an effective and adaptable method for simulating the body motions involved in construction manufacturing tasks within a controlled environment. VR can provide situational training on real-world scenarios while posing negligible risk (Joshi et al. 2021; Pavlou et al. 2021). The application of VR to ergonomic analysis has been investigated in previous studies focusing on, for instance, workplace design (Azizi et al. 2018; Battini et al. 2018; Dias Barkokebas et al. 2022; Dias Barkokebas and Li 2021; Peruzzini et al. 2016) and industrialized construction tasks (Dias Barkokebas et al. 2020; Dias Barkokebas and Li 2021). Moreover, the integration of VR with a motion capture (MOCAP) system—a system used to collect precise information on body motions—allows for ergonomic risks to be accurately assessed with the added benefits of not disrupting the production line and not exposing workers to actual hazardous situations(Dias Barkokebas et al. 2022; Joshi et al. 2021). However, despite advancements in the use of VR in conjunction with MOCAP in ergonomics applications, the integration of these technologies to provide training on industrialized construction tasks focusing on both ergonomics and operational aspects still requires investigation.

In this context, the aim of this study is to introduce a method to provide real-time, evidence-based ergonomic risk assessment integrated with postural recommendations as part of training on industrialized construction tasks through the combination of VR simulation and MOCAP sensors—the "*SmartVRErgo*". For this purpose, two existing rule-based ergonomic risk evaluation methods, the Rapid Upper Limb Assessment (RULA) (McAtamney and Corlett 1993) and the Rapid Entire Body Assessment (REBA) (Hignett and McAtamney 2000), are used to evaluate postural ergonomic risks based on joint angles. In addition, other physiological measurements—

i.e., heart (HR) and respiration rates (RR)—are collected for the purpose of physical fatigue analysis, and a questionnaire is administered to acquire subjects' perception of the VR simulation and of the physical and mental workload of the task. This study's contributions to the body of knowledge are: (1) the development of a method to provide automated, real-time postural ergonomic assessment and operational training on industrialized construction tasks through VR simulation (within this proposed method, subjects complete a task immersed in the virtual environment while their body motion data is not only collected but also processed in real time; additionally, their HR, RR, and questionnaire responses are integrated to achieve a thorough ergonomic assessment of the task), and (2) an empirical evaluation of the effectiveness of the proposed method in decreasing subjects' exposure to ergonomically hazardous postures in a pre-test/post-test procedure in conjunction with a randomized control group research experiment.

6.2. Background

6.2.1. Real-time Ergonomics Recommendations during Training

Based on a review of existing literature, Lim and D'Souza (Lim and D'Souza 2020) assert that relatively few studies have investigated the use of a MOCAP system to simultaneously assess ergonomic risks while providing subjects with ergonomics recommendations in real time during the completion of a task. In the few existing studies in this area, the use of inertial measurement units (IMUs), whether attached to a vest (Cerqueira et al. 2020) or to personal protective equipment used on site (Yan et al. 2017) or integrated with augmented reality for industrial applications (Vignais et al. 2013), is proposed as a means of providing real-time ergonomic feedback to subjects while tasks are being performed. Other studies have proposed real-time posture estimation and classification using cameras (e.g., Kinect system) to collect human body motion data (Konstantinidis et al. 2021; Mgbemena et al. 2018; Ray and Teizer 2012).

In the aforementioned studies, the subject's self-awareness of postural ergonomic risks is improved; however, a notable drawback of these studies is that subjects are exposed to on-site ergonomic risks during the evaluation process, as tasks are performed in the real world. Therefore, there remains a need for a real-time ergonomic system that provides ergonomics recommendations to workers during training sessions intended to assess ergonomic risks and increase subjects' awareness of ergonomically hazardous postures without interfering in the productivity of the production line while providing a comprehensive understanding of the impacts of postural changes on exposure to ergonomic risks. Furthermore, the effectiveness of proposed ergonomics recommendations with respect to the execution of a task is evaluated in these existing studies by comparing the pre-intervention phase with the intervention phase. As such, the task is analyzed while being executed without ergonomics recommendations and then during the intervention with ergonomics recommendations being provided to the subject. However, the effect of providing ergonomics recommendations on the ability of subjects to avoid ergonomically hazardous postures in the post-intervention phase is a gap yet to be explored.

VR supports comprehension of concepts in a three-dimensional (3D) and immersive environment through the replication of real-world stimuli (Chen et al. 2011). Indeed, in VR applications, large-scale and complex scenarios, such as industrialized construction facilities, can be represented at a full scale (i.e., 1:1) encompassing user interactions existing in the real world (Dücker et al. 2016). In this context, VR can provide situational training with only a negligible amount of risk compared to real-world training (Barkokebas et al. 2019; Joshi et al. 2021). In fact, according to the literature review carried out by Pan et al. (Pan et al. 2007), VR can motivate and stimulate learners to better comprehend real-life events compared to traditional paper-based training. Specifically with respect to training on construction tasks, the effectiveness of using VR for training has been evaluated in comparison with conventional paper-based training on a maintenance task (Barkokebas et al. 2019), and VR applications are proposed to unforeseen construction issues often resultants from stakeholders' decision (Goulding et al. 2012) and to teach safe postures for lifting tasks (Ojelade and Paige 2020). In a recent study, Pavlou et al. (Pavlou et al. 2021) propose a framework for interactive training and ergonomic assessment based on a digital human model and VR, recommending the use of a MOCAP system to increase the accuracy of the analysis. Although previous studies have verified the effectiveness of VR for training purposes, though, the application of this technology to provide real-time ergonomics recommendations during training on industrialized construction tasks still requires investigation.

6.2.2. Existing Methods for Human Physiological Measurements Monitoring

Early identification of physical fatigue and ergonomic risks in industrialized construction facilities is essential to avoid WMSDs and increase efficiency, especially considering an ageing workforce and increasing labour costs (Yu et al. 2019). Physical fatigue can be defined as "a reduction in capacity to perform physical work" (Gawron et al. 2001) due to sustained physical demand. In industrialized construction, physical fatigue is typically caused by forceful exertion and repetitive manual handling motions combined with prolonged work hours without proper break periods (Umer et al. 2020). If situations likely to generate fatigue can be identified and anticipated, interventions such as timely rest periods can be implemented to reduce the detrimental impact of physical fatigue on worker health, work quality, and overall productivity (Umer et al. 2017). Indeed, Gatti et al. (Gatti et al. 2014a) suggest that controlling workers' physical stress as a way of preventing fatigue is an important management approach. In this regard, the use of HR and RR to evaluate physical exertion and fatigue levels of construction workers has been explored extensively in previous research studies (Anwer et al. 2021; Chang et al. 2009; Gatti et al. 2014b; S. and G. 2002; Wong et al. 2014). During physical exertion, increased blood flow is requested by muscles, and this results in a rise in HR and RR. For this reason, average and peak HR, heart-rate variability (HRV), electromyography (EMG), average RR, and oxygen consumption are considered to be acceptable metrics for assessing physical fatigue and exertion (Zhu et al. 2017).

Traditional methods for analysis of postural ergonomic risk, meanwhile, can be classified as either observation- or instrument-based (Mgbemena et al. 2018). Observational methods rely on data collected through subject observation; these methods focus mainly on postures, and are prone to biased results due to the subjective nature of the data collection—i.e., visual perception of body motions (Roman-Liu 2014). Instrument-based methods, on the other hand, use instruments such as sensors or markers attached to the human body, computer-vision methods, or range cameras to collect information on body motions (Bortolini et al. 2018). This means that the data is collected automatically and in a precise manner, but the post-processing can be time-consuming (Wang et al. 2015). Most MOCAP systems are classified as direct instrument-based methods since sensors or markers are attached directly to the human body. The use of an instrument-based system such as a MOCAP system to collect body motion data has been recommended as a way to increase the accuracy of postural assessments (Pavlou et al. 2021). Inertia MOCAPs offer the advantage of being able to estimate body movements without the need for a visual field, thereby reducing the risk of inconsistency in the resulting data due to obstructions caused by operational motions (Bortolini et al. 2018; Fletcher et al. 2018).

6.2.3. Existing Methods for Ergonomic Risk Assessment

RULA, REBA, Ovako Working-posture Assessment System (OWAS), and the Washington Industrial Safety and Health Act (WISHA) Caution/Hazard Zone Checklist are all examples of well-established methods for ergonomic risk assessment. Among these, both RULA and REBA are frequently used in research studies, as they are capable of calculating a total risk score by combining the sub-scores per body segment, force load, and muscle activity (Hignett and McAtamney 2000; McAtamney and Corlett 1993). The total RULA score provides a qualitative risk assessment as follows: 1 to 2 = acceptable posture; 3 to 4 = further investigation required, changes may be needed; 5 to 6 = further investigation is required, change soon, and 6+ = investigate and implement change (McAtamney and Corlett 1993). The total REBA score, meanwhile, is assessed as follows: 1 = negligible risk; 2 to 3 = low risk; 4 to 7 = medium risk; 8 to 10 = high risk; 11+ = very high risk (Hignett and McAtamney 2000). Based on the results of a sensitivity analysis conducted to verify the impact of each sub-score on the RULA and REBA total risk score, Escobar (Escobar 2006) concludes that the most critical body segments for RULA are the upper arm, neck, trunk, and legs, while those for REBA are the trunk, upper arm, legs, neck, and wrist. This finding aids in the selection of key body segments to be monitored in real time during the completion of a task.

In the present study, RULA and REBA are selected as the risk assessment methods by which to perform postural ergonomic analysis (using body motion data from an inertia MOCAP system obtained while simulating an operational task in an immersive VR environment). The total RULA and REBA scores are calculated automatically in real time during the simulation of the task, HR and RR are analyzed to verify fatigue and workload levels, and a questionnaire is used to acquire participants' perceptions of the VR simulation and of the mental and physical workload of the task.

6.3. Methods

6.3.1. Overview of the Research Methods Employed

A pre-test/post-test procedure with a randomized control group is applied to validate the method proposed in the present study. This approach is chosen for the present study since it has been recommended in the literature as a suitable method for measuring the effectiveness of deploying a given intervention, since data pertinent to dependent variables can be collected before, during, and after the intervention is implemented (Williamson and Johanson 2018). In addition, the use of repeated measurements (i.e., pre-test, intervention, and post-test) increases the power and precision of the analysis, as each subject can establish their own performance benchmark (Hunter and Schmidt 2015). For these reasons, this approach has been applied in previous ergonomic research to assess the benefits of implementing proposed interventions (Gholami et al. 2020; Hemati et al. 2020; Partido and Henderson 2021). Although maturation and learning effects are potential drawbacks of a pre-test/post-test procedure with a randomized control group (Williamson and Johanson 2018), both the intervention and control groups are equally susceptible to these effects, and thus they are unlikely to distort the results.

As illustrated in Figure 6.1, this experimental research is carried out in four phases as defined in the pre-test/post-test methodology (Williamson and Johanson 2018). As shown in the figure, the inputs to the methodology are identification of the research gap and definition of hypothesis, objectives, intervention, and dependent variables. In the present study, two gaps are identified based on a review of the relevant literature: (a) investigation of the use of VR for simultaneously assessing the ergonomic risks inherent in an operational task and providing real-time ergonomics recommendations to the subject, and (b) verification of the effectiveness of ergonomics training to improve the subject's awareness of ergonomically hazardous postures. In this context, this study is built upon the hypothesis that *a subject will spend less time exposed to ergonomic risks in the high-risk range in training sessions in which ergonomics recommendations are provided in real time in the VR scene, as the subject will be more aware of ergonomically hazardous postures*. To test this hypothesis and fill the identified research gaps, the objective of this study is twofold: (1) develop a method, named *SmartVRErgo*, to provide real-time ergonomics recommendations during training on industrialized construction tasks through the integration of VR and MOCAP, and (2) verify the effectiveness of the SmartVRErgo to reduce exposure to ergonomic risks in the "high-risk" range categories in RULA and REBA. As such, the proposed method is the intervention of the research experiment. The dependent variables used to measure the effectiveness of the intervention are the total RULA and REBA scores, the RULA and REBA sub-scores of flexion angles of key body segments, HR, RR, and responses to a questionnaire on subjects' perceptions of the physical and mental workload of the task.

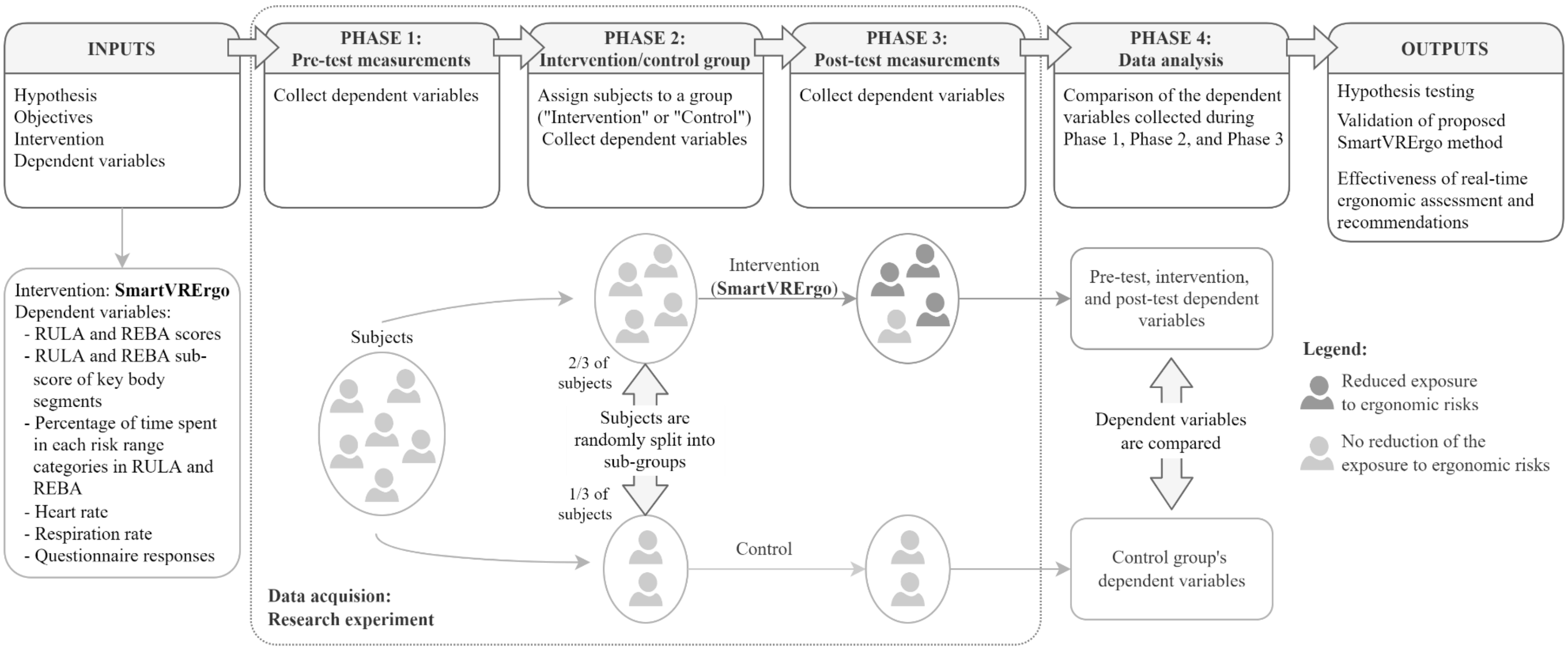


Figure 6.1: Overview of the research methods.

With ethics approval, prospective subjects are invited prior to Phase 1 to voluntarily participate in the research experiment (the invitation having been distributed by email to engineering students at the authors' institution). Before subjects begin the experiment, they are given instructions on how to use the VR hand controllers, how to interact with elements within the VR scene, and how to complete the task. In Phase 1, all subjects receive the same training without postural ergonomics recommendations. This sets the benchmark for measuring the effectiveness of the proposed SmartVRErgo method in reducing the exposure to ergonomic risks in the high-risk range. In Phase 2, subjects are divided into two groups by randomly picking a number from a spreadsheet: one group that receives the intervention and another group (i.e., the control group) that receives the training without ergonomics recommendations. A 2:1 ratio in terms of the number of subjects between intervention group and control group, it should be noted, has been used in confirmatory trials in which a higher number of subjects receiving the intervention is needed in order to, for instance, monitor the impact of the intervention on subject's learning and health (Hey and Kimmelman 2014; Torgerson and Campbell 1997). Given that the effect of the proposed method on the behaviour of subjects in the intervention group is one of the primary factors to be analyzed in the present study, the 2:1 ratio is chosen for dividing the subjects into intervention and control groups. In Phase 3, both groups receive the same training without ergonomics recommendations. A break is provided between the phases of data acquisition in order to avoid onset of fatigue and increased stress levels. In Phase 4, the effectiveness of receiving training with real-time ergonomic assessment and recommendations in the VR scene is evaluated in relation to the pre-test measurements (i.e., ergonomic assessments of the same subjects before and after being exposed to the intervention), intervention measurements, and control group. As such, the hypothesis of this study can be verified based on quantitative (i.e., RULA, REBA, and HR and RR) and qualitative (i.e., questionnaire responses) evidence collected throughout Phases 1, 2, and 3. The internal validity of the results is ensured by (1) confirming that the only aspect that changes between the training received by the two groups is the addition of the ergonomics recommendations and (2) having a randomized control group. Accordingly, the differences between the ergonomic assessments of the two groups can be attributed to the intervention and not to other external factors (Robson 2001).

6.3.2. Proposed SmartVRErgo Method

The inputs of the proposed SmartVRErgo method are information on the task to be simulated, which includes tools and equipment required, hierarchical sequence of activities, and workstation design; evaluation criteria of existing ergonomic risk assessment methods—i.e., RULA and REBA; relevant subject information required as inputs to the MOCAP software; and a preliminary assessment of the ergonomic risks of the simulated task. As illustrated in Figure 6.2, the main processes underlying the proposed SmartVRErgo method are: (1) VR model design, (2) data acquisition, and (3) data analysis; (these processes are further detailed in the following subsections). The outputs of the proposed method are the total RULA and REBA scores; the RULA and REBA sub-scores per body segments; fatigue and physical workload analyses; evaluation of subjects' perceptions of the designed VR simulation; and the provision of ergonomics recommendations during training in a controlled VR environment.

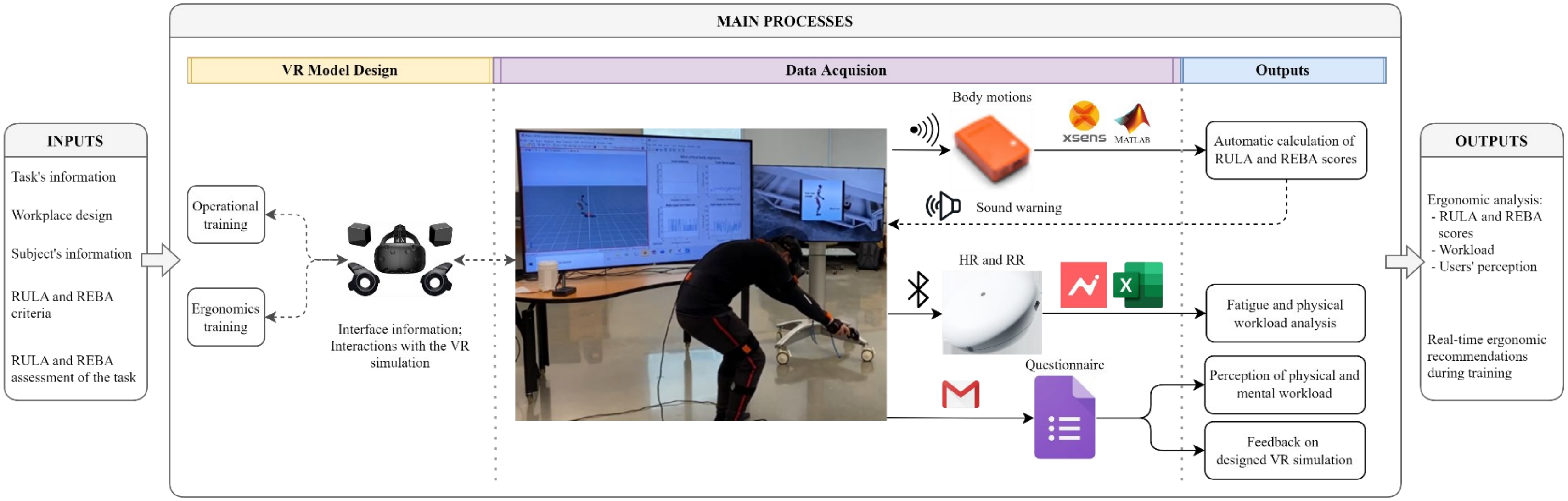


Figure 6.2: Overview of the proposed SmartVRErgo method.

6.3.2.1. VR Model Design

In this study, an HTC VIVE VR system that includes a headset, two wireless hand controllers, and two wireless base stations is used as the VR system. Interactions and visualization features in the VR environment are determined in the Unreal Engine (version 4.22.3) software in order to simulate the motions associated with the task under study. These motions can include reaching, bending forward, and lifting objects weighing less than 2 kg (4.4 lb.). The hierarchy of events as observed in the task in the real world is included in the Unreal Engine, and events are triggered as the subject interacts with a piece of equipment or a tool within the virtual environment. By highlighting in green the step to be executed and indicating in cyan when relevant pieces of equipment are within the subject's reach or when the correct piece of equipment has been taken up by the subject, operational training is provided to the subject while they are immersed in the VR application.

The ergonomics recommendations are defined based on a preliminary assessment of the task being simulated in the VR environment, appearing in the VR scene as segmental demos, as exemplified in Figure 6.3. During the pre-assessment, a subject representing the 50^{th} percentile for stature among the female population in the United States (Anderson and Whitcomb 2017) performs the task without any ergonomics recommendation. Based on the ergonomic risk assessment of the subject's body motions, motions with higher ergonomic risks are identified. The 50^{th} female percentile for stature is chosen for the preliminary assessment since it covers a significant portion of the population, and since the subject satisfying this profile would be exposed to more ergonomic risks related to reaching motions (e.g., reaching pieces of equipment further away from the edge of the workstation resulting in an extended upper arm) due to her shorter stature in comparison with a subject representing the 50^{th} male percentile. Postural recommendations to avoid body motions associated with joint angles within high-risk range of sub-scores in RULA and REBA, and that account for ergonomic principles such as recommended distances to ensure reachability of items at a workstation, are provided accordingly. In addition to these criteria, the ergonomics recommendations are proposed in consideration of the lowest level of ergonomic risk that can be achieved without changing workstation design parameters and/or modifying operational procedures. As such, the threshold used to trigger the segmental demos is to be adapted for every task based on the pre-assessment for the given task. The segmental demos are inputted to the game engine software in such a manner that they are hidden in the VR simulation. In order for them to appear on the virtual screen, a specific trigger button on the keyboard must be pressed by the training session coordinator once the sound warning is triggered by the real-time assessment of ergonomic risks. Once the recommendations have appeared on the virtual screen, they disappear automatically when the segmental demo ends.

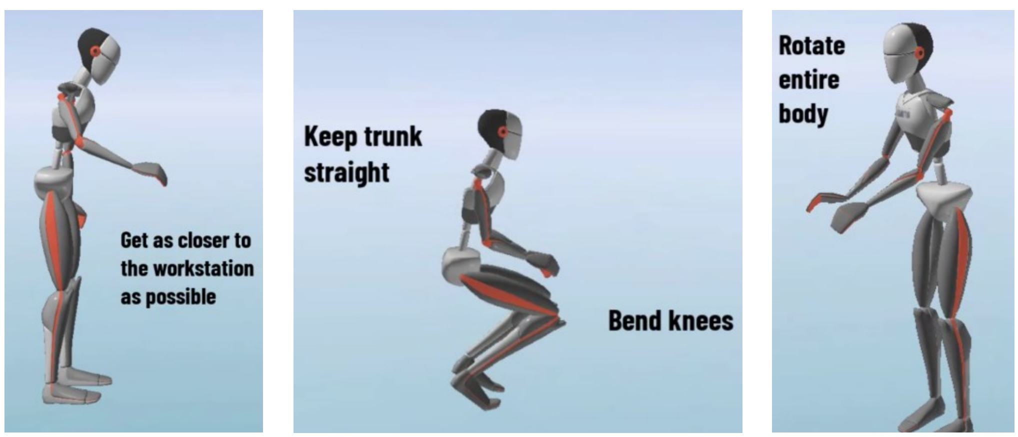


Figure 6.3: Sample of ergonomics recommendation included in the VR application.

6.3.2.2. Data Acquisition

While the subject is immersed in the VR environment, their body motions and physiological measurements are collected using a MOCAP system and a medical tracker device, respectively. Xsens MTN Awinda is chosen as the MOCAP system, as it is capable of collecting precise body motion data via wireless IMUs and allows the subject to move freely while engaged in the VR environment [60]. The Xsens MTN Awinda consists of a wireless station receiver, a segmometer, and seventeen IMUs affixed in predetermined locations of the human body using motion track full-body Velcro straps. Meanwhile, Aidmed is chosen as the medical tracker device for capturing HR and RR, since it is a non-intrusive, comfortable, and accurate chest strap device that provides reliable results without altering the subject's activity (which is notable considering that the intrusiveness of the measurement equipment can be detrimental to the reliability of the data obtained) (Aidlab 2021). The HR and RR data are analyzed once the task has been simulated. Finally, the user's perceptions are solicited using an online questionnaire (administered using Google Forms) focusing on two aspects: the subject's perception of the task and their perception of the developed VR model.

With respect to the body motion data, the 17 IMUs provide information on 66 joint angles, including horizontal and vertical axes, and their output frame rate is 60 Hz. The biomechanical rigged character in MVN Analyze software is composed of twenty-eight rigid segments (one for hips; four for chest; one for neck; two for the head; and one for each collar, shoulder, elbow, wrist, hip, knee, ankle, toe, and toe end). This character provides twenty degrees of freedom as follows: three for each shoulder, for the neck, and for trunk; and two for each elbow and each wrist. In the proposed method, only the angles relevant to the RULA and REBA assessments—20 angles total when including both sides of the body—are taken into consideration in the analysis. In addition to the MOCAP, video recording devices are used during the experiment as a supplement in the event of inconsistent body motion data from the MOCAP system. To capture HR and RR, the subject wears an Aidmed device on their chest throughout the training session. The Aidmed data is synced in real time to the Aidlab mobile app, which uploads the data to the Aidmed Cloud. From the Aidmed Cloud, the data is downloaded to Excel.

In the questionnaire, the questions concerning the VR environment focus on the degree of immersiveness, safety, and engagement perceived by the subject during the VR simulation, as well as on measuring the visual accuracy of the VR environment from the subject's perspective. The questions soliciting input on the perceived workload of the task, meanwhile, are based on the NASA-Task Load Index (TLX) questionnaire, which includes six categories: mental, physical, and time demands; performance; effort; and frustration level (Hart and Staveland 1988). Respondents rate their responses using a 7-point Likert scale. Following the protocol defined by Peruzzini et al. (Peruzzini et al. 2020) and the NASA-TLX (Hart and Staveland 1988), the questions below are included in the questionnaire:

Q.1: How much mental activity was needed to complete the task?

Q.2: How much physical activity was demanded is the task?

Q.3: How hurried or rushed is the pace of the task?

Q.4: How successful do you think you were in accomplishing the task?

Q.5: How hard did you have to work to accomplish your level of performance?

Q.6: How insecure, discouraged, irritated, stressed, and annoyed were you during the task?

6.3.2.3. Data Analysis

6.3.2.3.1. Postural Ergonomic Analysis

In the proposed SmartVRErgo method, ergonomic analysis is carried out primarily in consideration of the subject's postures. The real-time automated RULA and REBA analyses are carried out by streaming the motion data from Xsens MVN Analyze software to MATLAB software. The real-time RULA and REBA assessments allow for the subject to be signaled with a sound warning when a pre-defined risk level is surpassed. In this manner, the proposed method provides not only ergonomics recommendations but also real-time feedback on the exposure to ergonomic risks in the high-risk range in RULA and REBA.

The literature recommends the use of a paired *t*-test when the difference between two variables for the same subject is the target of the analysis (Albassam and Aslam 2021). Therefore, to verify the impact of the proposed SmartVRErgo on reducing exposure to ergonomic risks, the paired *t*-test method is applied to the pre-test and post-test data for the intervention group, as well as to the data from the first and third interactions with the VR simulation for subjects in the control group. Because the Welch's *t*-test is recommended in the literature for unpaired data of two groups of different sample sizes (Delacre et al. 2017), this test is applied in the present study to verify that there is a statistically significant difference between the intervention and the control group. Both *t*-tests are performed with a 95% confidence interval.

6.3.2.3.2. Post-analysis of Fatigue, Physical, and Mental Workload

Fatigue and physical workload are analyzed based on the HR and RR data and the questionnaire responses. The average HR is used for workload classification as per the approach proposed by Astrand and Rodahl (Åstrand and Rodahl 1986), shown in Table 6.1. RR is analyzed taking into consideration the normal RR for healthy adults, which is between 6 to 30 breaths per minute (bpm)

(Jaiswal et al. 2019). An RR exceeding this range during the training indicates that the task or the workstation design should be reviewed.

Table 6.1. Classification of fatigue based on HR.

Astrand and Rodahl (1986) classification	
HR (beats per minute)	**Workload classification**
< 90	Light work
90 ≤ HR < 110	Moderate work
110 ≤ HR < 130	Heavy work
130 ≤ HR < 150	Very heavy work
150 ≤ HR < 170	Extremely heavy work

The subjects' perceptions of the physical and mental demands of the task are measured based on the average ($\tilde{x}$) rating on the 7-point Likert scale (i.e., very low = 1; very high = 7) of the responses to the questions presented in Subsection 6.3.2.2. As such, a $\tilde{x}$ rating of the responses to Q.1, Q.2, Q.3, Q.5, and Q.6 that is above 6 (6 representing "high" in the 7-point Likert scale) indicates that the subjects feel that the task requires a high level of effort, that they feel discouraged while completing the task, and that they perceive the task as being highly mentally and physically demanding, and with a high speed. On the other hand, a $\tilde{x}$ rating in response to Q.4 that is above 6 suggests that subjects are satisfied with their performance during the task.

6.4. Case Study

6.4.1. Description

As a case study, the proposed SmartVRErgo is deployed to simulate the disassembly of the drilling module of a semi-automated wall framing machine. The ergonomic analysis is conducted for the entire operation process. Although lifting of machinery pieces is required during the task, these items weigh less than 2 kg each, so their weight does not alter the total RULA and REBA scores (McAtamney and Corlett 1993). Table 6.2 provides further information on the task used as a case study. The VR scenario for this task represents an industrialized construction facility and features a wood framing machine, a cart with tools needed to complete the task, and a table on which to place the pieces of equipment during the disassembly process. All pieces of equipment are placed on the table except the drilling case (Subtask 7) and the compact drilling machine (Subtask 8), which are placed on a shelf in the middle of the cart. The experiments are carried out in a laboratory space with an unobstructed area of 2.60 m × 3.80 m.

Table 6.2. Description of subtasks and tools required to complete the task.

	Subtask 1 Remove screw from drilling clamp	**Subtask 2** Remove drilling clamp	**Subtask 3** Loosen bolts of supporting bar	**Subtask 4** Remove supporting bar	**Subtask 5** Remove side screws from drilling case	**Subtask 6** Remove bolt from drilling case	**Subtask 7** Remove drilling case	**Subtask 8** Remove drill
Virtual hand(s)		■		■			■	■
Allen key	■		■		■			
Wrench						■		

6.4.2. Pre-assessment of Ergonomic Risks

The results of the pre-assessment indicate that the dominant upper arm, trunk, and neck are the body segments bearing most of the physically demand. When performing the task following certain ergonomics recommendations, a reduction in the exposure to high-risk range RULA and REBA sub-scores is observed for both the upper arm and the trunk. However, no reduction in the RULA and REBA sub-scores for the neck is observed as a result of the ergonomics recommendations. For this reason, and considering that the top three body segments in terms of their impact on total RULA score are the upper arms, neck, and trunk, while the top three in terms of contribution to total REBA score are the trunk, upper arms, and legs (Escobar 2006), sound warnings are defined for the trunk and upper arm flexion angles. These sound warnings are triggered when the subject is exposed to the sub-scores defined in Table 6.3. Along with the sound warning, ergonomics recommendations are presented to the subject in the VR scene. These recommendations are provided through segmental demos with durations between 2 and 8 seconds. The recommendations include rotating the entire body while moving hardware components from the wall framing machine to the table; positioning oneself as close as possible to the workstation when completing lifting tasks in order to reduce ergonomic risks in the upper arms; and bending the knees rather than the trunk while positioning larger hardware components in the cart (Subtasks 7 and 8).

Table 6.3. Thresholds for triggering the sound warning based on RULA and REBA for the case study.

Body segment	Thresholds sub-score RULA and REBA
Trunk (flexion angle score)	= 4
Upper arm (flexion angle score)	≥ 3

6.4.3. Subjects

The research methods described in Subsection 6.3.1 are followed during the experiment. Altogether, 38 subjects check in for participation—17 female and 21 male—with an average height of 173 cm and a standard deviation (σ) of 9 cm, most of the subjects (35 of 38) being right-handed. The 38 subjects are randomly divided into an implementation group and a control group according to the 2:1 ratio mentioned above, with 24 subjects completing the training with the proposed SmartVRErgo method applied and 13 subjects completing the training only with operational instructions.

6.4.4. Results and Discussion

Among the 38 subjects, the body motion data from 37 subjects is used to conduct the postural risk assessment. The data from one subject (ID 19) from the intervention group is removed from the data analysis due to discrepancies between the body motion data from the MOCAP system and the motions observed in the recorded video. For the remaining 37 subjects, body motion data from the dominant side of the subject's body is used in the analysis. In terms of questionnaire results, responses from 33 subjects are used in the analysis (since 5 subjects did not submit responses to the questionnaire). The HR and RR are collected for all subjects; however, only data from 32 subjects are used in the analysis since the data of 6 subjects (3 from the implementation group and 3 from the control group) is discarded due to readings either inconsistent with normal values of HR and RR or with several gaps in the data.

6.4.4.1. Percentage of Time Spent in Each RULA and REBA Risk Range

As described in Subsection 6.2.3, the RULA and REBA total scores are translated into four and five, respectively, risk levels. In this subsection, the percentage of time spent by each subject in each risk level is analyzed for the dominant side of the body to verify whether subjects that received the training with ergonomics recommendations spent less time in ergonomic risks in the high-risk range than subjects who were not presented with the recommendations. Figure 6.4 and Figure 6.5 detail the distribution of time spent in each RULA and REBA risk level, respectively. It should be noted that, although both RULA and REBA have a "negligible" risk level, no subjects spent time in this risk level since they began the experiment either looking down (neck angle > 20°) or looking up (neck angle < 0°). For this reason, the "negligible" category is not shown in Figure 6.4 and Figure 6.5. As observed in Figure 6.4, there is a reduction of 35% in time spent in the RULA high risk level when comparing the average time spent in this risk level in the pre-test versus post-test data. The result of the paired *t*-test confirms a significant ($p < 0.006$) reduction in the time spent in the RULA high risk level in the group that received training through the proposed SmartVRErgo method (i.e., intervention) when comparing the pre-test and post-test data of subjects from this group. On the other hand, the paired *t*-test does not identify a significant reduction in the time spent in the REBA high ($p = 0.457$) and very high ($p = 0.306$) risk levels. As noted in Figure 6.4 and Figure 6.5, when subjects complete the task without the SmartVRErgo (i.e., control group), the percentage of time spent in ergonomic risks in the high-risk range does not change significantly for RULA ($p = 0.056$) and REBA ($p = 0.475$ for high risk level, and $p = 0.383$ for very high risk level) assessments.

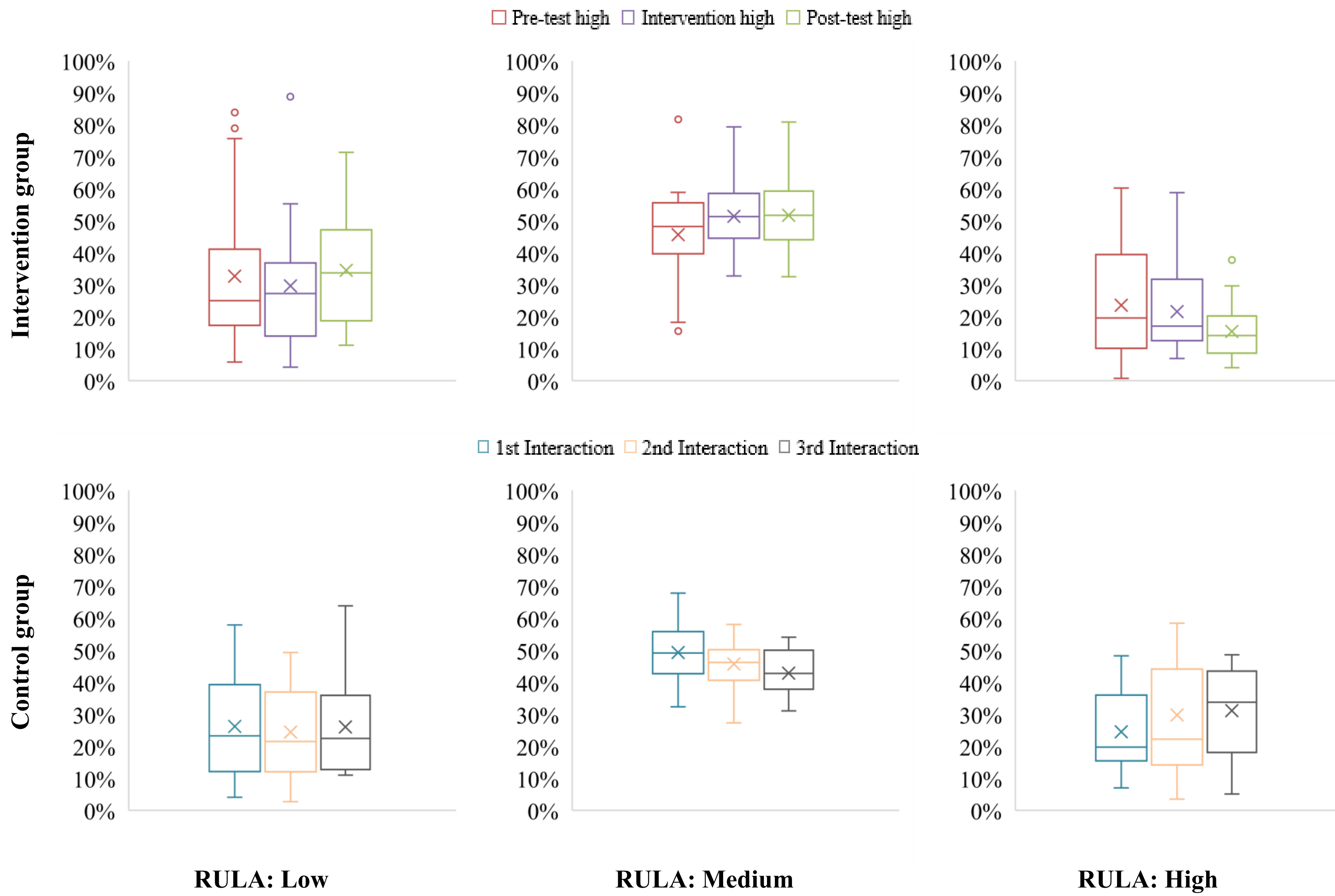


Figure 6.4: Distribution of time spent in each RULA category of risk level.

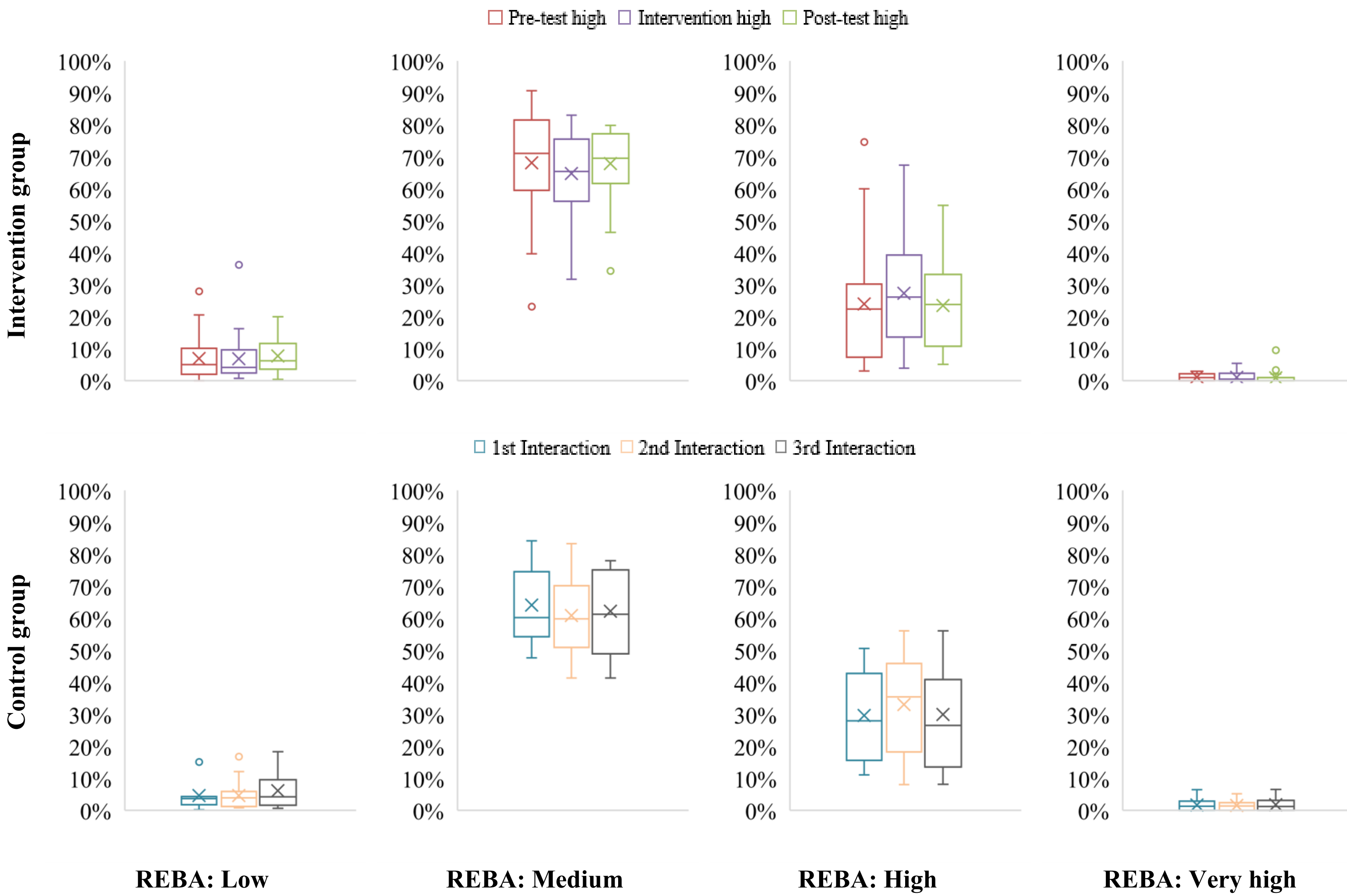


Figure 6.5: Distribution of time spent in each REBA category of risk level.

The Welch's *t*-test reveals that there is a statistically significant difference between the two groups with respect to the percentage of time spent in high risk level based on RULA assessment (p = 0.002) but not based on REBA assessment (p = 0.239 and p = 0.248 for high and very high risk levels, respectively). The findings of the research experiment indicate that the reduction in the percentage of time spent in high-risk range levels when deploying RULA is attributed to the proposed SmartVRErgo method; however, the impact of the proposed method on REBA is not evidenced by the pre-test/post-test data. This result can be explained by the fact that most of the ergonomics recommendations provided by the proposed method focus on reducing the extension of the upper arm during the completion of the task; upper arm is the most critical body segment in terms of its impact on RULA total score, as per the sensitivity analysis conducted by Escobar (Escobar 2006).

6.4.4.2. RULA and REBA Total Score

The average RULA total scores for the dominant side of subjects in the intervention group are found to be 5.33 (σ = 0.74), 5.36 (σ = 0.63), and 5.16 (σ = 0.49) for the pre-test, intervention, and post-test, respectively; while for the control group the averages are found to be 5.47 (σ = 0.51), 5.59 (σ = 0.59), and 5.54 (σ = 0.59) for the first, second, and third interactions with the VR simulation, respectively. The average REBA total scores for the dominant side of the body in the intervention group for the pre-test, intervention, and post-test are found to be 5.70 (σ = 0.99), 5.85 (σ = 0.91), and 5.50 (σ = 0.77), respectively; while, for the control group, these average scores are found to be 6.06 (σ = 0.66), 6.19 (σ = 0.77), and 6.31 (σ = 0.88), respectively. As shown in Figure 6.6, there is a reduction in both RULA and REBA total score among participants in the intervention group between the pre-test and post-test score. However, this reduction is not statistically significant, as per the paired t-test results (p = 0.101 for RULA and p = 0.176 for REBA).

Meanwhile, the Welch's t-test indicates that the difference between the two groups (i.e., intervention and control) is statistically significant for REBA (p = 0.010) total score and slightly less significant for RULA total score (p = 0.060).

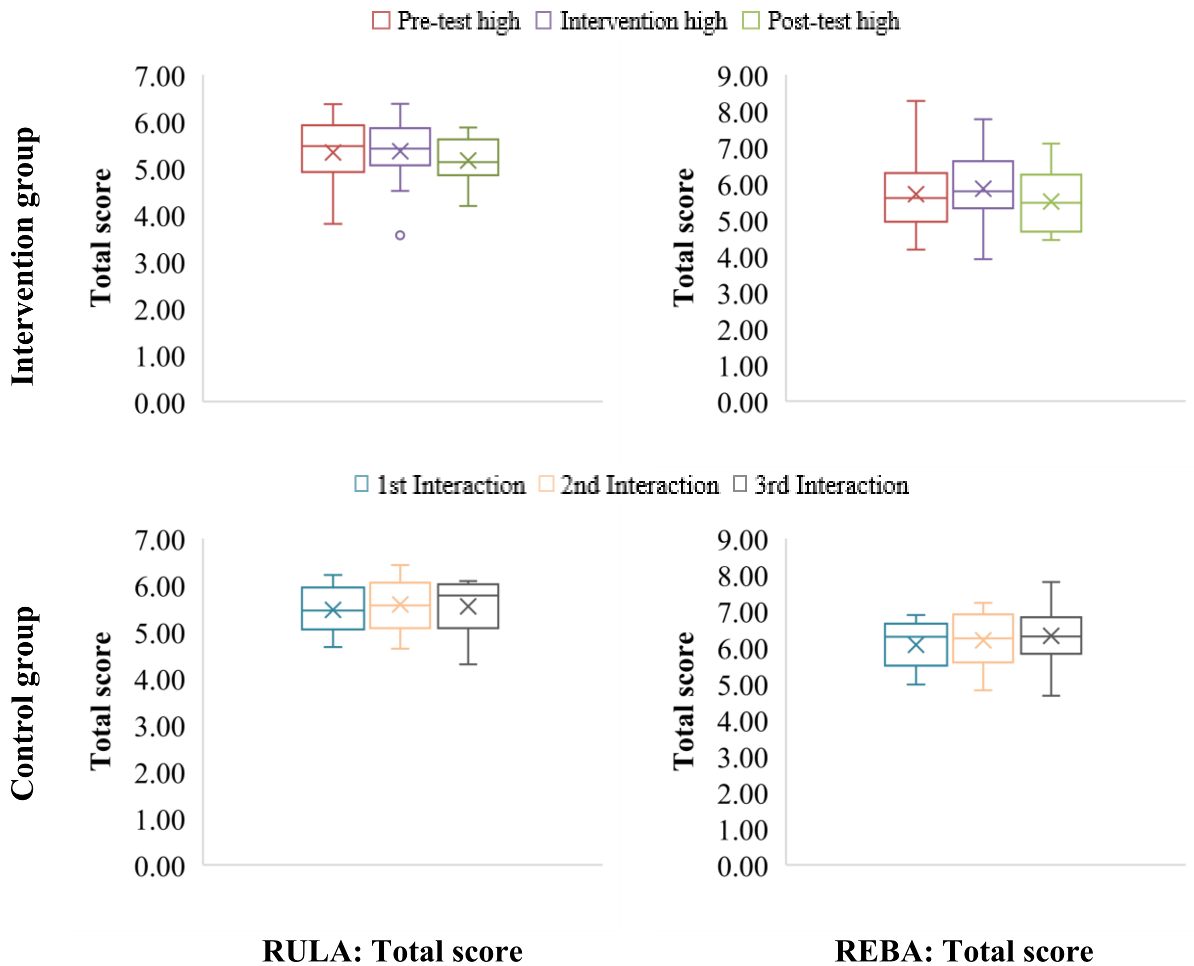


Figure 6.6: RULA and REBA total score for the entire task.

6.4.4.3. RULA and REBA Sub-scores of Relevant Body Segments

Both the dominant upper arm and the trunk are monitored during the completion of the task to observe whether the sound warning and segmental demos with ergonomics recommendations will be triggered. As such, their sub-scores are investigated to verify whether any reduction occurs. The average sub-scores of the dominant upper arm are 1.96 (σ = 0.30), 1.80 (σ = 0.24), and 1.71 (σ =

0.30) for the intervention group in the pre-test, intervention, and post-test, respectively, while, for the control group, the average sub-scores are 1.81 ($\sigma = 0.29$), 1.84 ($\sigma = 0.31$), and 1.88 ($\sigma = 0.31$) for the three rounds of interaction with the VR environment, respectively. A reduction of 9% is observed when comparing the average sub-score of the post-test to that of the third round of interaction of the control group. Similarly, the trunk average sub-score decreases by 5% between the average post-test sub-score and the sub-score of the last interaction of the control group. The average trunk sub-scores for the intervention group are 2.10 ($\sigma = 0.20$), 2.11 ($\sigma = 0.23$), and 2.02 ($\sigma = 0.03$), while for the control group they are 2.09 ($\sigma = 0.12$), 2.11 ($\sigma = 0.12$), and 2.12 ($\sigma = 0.14$).

In terms of statistical analysis, the paired *t*-test verifies a significant difference in the sub-score of the dominant upper arm ($p < 0.001$) and trunk ($p = 0.023$) between the pre-test and post-test results of the intervention group considering the average RULA and REBA sub-scores of these body segments for the entire task, while no statistical significance is observed in the control group when comparing the sub-scores of the trunk ($p = 0.256$) and dominant upper arm ($p = 0.260$) during the first and third interactions with the VR environment. Therefore, the effectiveness of the SmartVRErgo in reducing the sub-scores of key body segments is confirmed based on the experiments results. This finding, based on the data of 37 subjects, confirms the results of Vignais et al. (Vignais et al. 2013), who identified a reduction in the RULA sub-score for the upper body when real-time ergonomic assessment was provided using augmented reality in a case study with only 12 subjects.

6.4.4.4. Questionnaire Responses

As detailed in Figure 6.7, subjects evaluate the task as being of low physical and mental demand and having a slow pace. In addition, subjects report feeling highly satisfied with their performance, safe, immersed, and engaged in the VR application, while not feeling stressed or insecure when completing the task. In terms of the usability of the VR environment, subjects report agreement that the VR application is intuitive and provides an accurate representation of reality, as detailed in Figure 6.8. Subjects also report strong agreement that the tools and equipment required to complete the task are easily visible and identifiable, that the VR application provides a good understanding of the task, and that their body motions in the VR environment were similar to those in the real world. It should be noted that the questionnaire also contains an area where subjects can provide free-form comments on their experience; a suggestion made here by a subject to include background noise in the VR applications similar to what would be found in a comparable environment in the real world will be considered in future work.

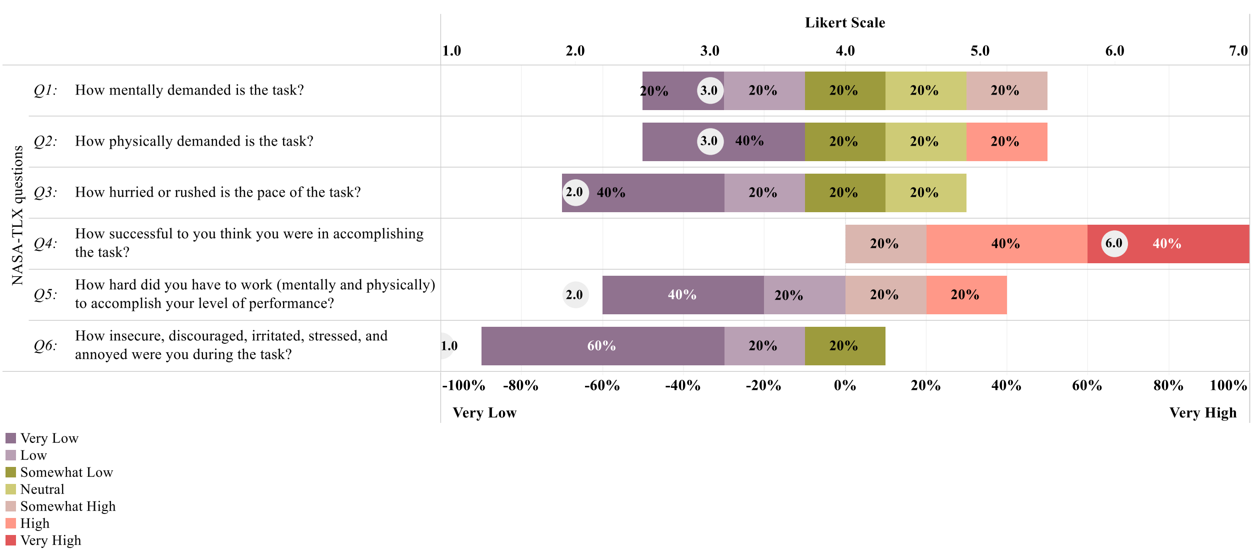


Figure 6.7: Subject's perception of physical and mental demands of the task based on NASA-TLX method.

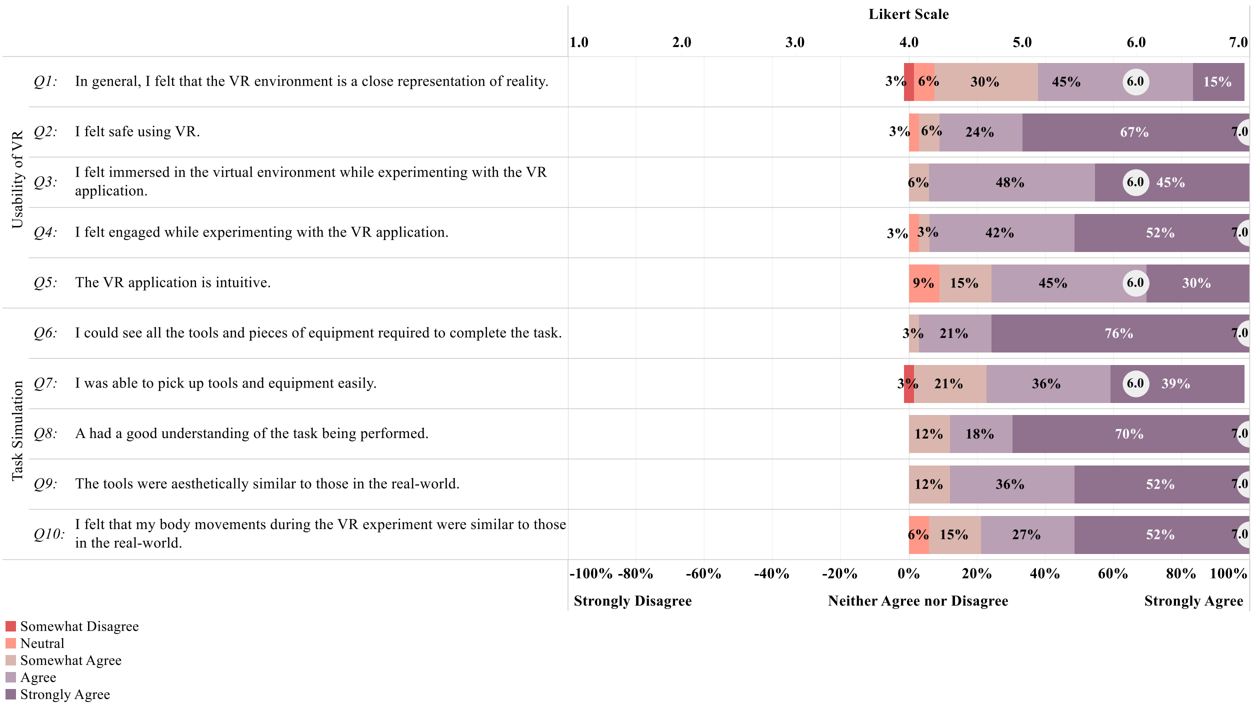


Figure 6.8: Questionnaire responses in terms of usability of VR and task simulation.

6.4.4.5. HR and RR Analysis

The average HR during the three rounds of interaction with the VR application is found to be 92 bpm ($\sigma = 13$) for the intervention group and 95 bpm ($\sigma = 13$) for the control group. As such, it is verified that the task has a moderate workload, as per the classification detailed in Table 6.1 (Subsection 6.3.2.3.2). The average RR is found to be 22 bpm ($\sigma = 2$) for the intervention group and 23 bpm ($\sigma = 2$) for the control group, both of these averages falling within the normal range of RR for healthy adults (Jaiswal et al. 2019). Based on the results of the Welch's *t*-test, there is not a statistically significant difference in average HR ($p = 0.530$) and RR ($p = 0.460$) between the subjects from the intervention and those from the control group. To verify whether the proposed SmartVRErgo has an impact in terms of reducing HR and RR, the implementation of the proposed method in a more physically demanding task is required.

6.5. Limitations and Future Work

Overall, the results of the pre-test/post-test experiment demonstrate that there is a significant reduction in exposure to ergonomically hazardous postures, particularly with respect to the upper body, when the training is completed through the proposed SmartVRErgo. However, it is important to mention that the proposed method does not consider time and forceful exertion factors during the analysis. For instance, the simulated task does not include the lifting and/or handling of materials weighing more than 2 kg. To address this limitation, the use of mixed reality will be pursued in future studies to simulate more physically demanding tasks in industrialized construction. It is also worth mentioning that, in the present research, HR and RR are analyzed for the entire experiment, so the calculation of the average includes the rates of the three rounds of interactions with the VR environment. For this reason, the pre-test and post-test data of HR and RR is not compared in this study. The deployment of the proposed SmartVRErgo in tasks that are more physically demanding is required in order to determine whether the proposed SmartVRErgo can significantly reduce HR and RR (as it did in the case of the RULA and REBA sub-scores of the key body segments monitored during the training session).

It is expected that the results of the thorough ergonomic assessments that can be obtained using the proposed method will support the design of appropriate work–rest schedules for various industrialized construction tasks as a way of avoiding severe effects of fatigue. By controlling and managing physical exertion based on evidence-based assessments conducted in a VR environment, various work–rest scenarios can be simulated as a part of broader ergonomics, productivity, and scheduling analysis initiatives. The application of the proposed method for the analysis of work–rest schedules will be investigated in future work. Future work will also investigate the elemental motions observed in industrialized construction tasks performed in the VR environment as a means of identifying acceptable sway magnitudes for the flexion, axial, and side rotation angles when calculating RULA and REBA scores.

6.6. Conclusion

This study proposes a method, SmartVRErgo, to provide real-time, evidence-based ergonomic risk assessment during training on industrialized construction tasks enabled by the integration of VR simulation with a MOCAP system. By assessing postural ergonomic risks in an automated and real-time manner deploying both RULA and REBA methods, ergonomics recommendations can be provided to subjects in a timely manner during training sessions. Subjects receive both ergonomics and operational training while immersed in the VR application. In addition, heart and respiration rates are collected during the training sessions for post-analysis purposes, focusing on fatigue and physical workload assessments. A questionnaire is then used to solicit input on the subject's perception of the task based on their responses to questions formulated using the NASA-TLX method, as well as to solicit their input on the developed VR application itself. According to the findings and the questionnaire results it can be concluded that a thorough ergonomic assessment of the task is obtained by deploying the proposed SmartVRErgo.

Moreover, based on the results of the pre-test/post-test procedure with 37 subjects, it is verified that providing ergonomics recommendations during operational training is a worthwhile practice, as it aids the subject in identifying and mitigating ergonomic risks. A statically significant ($p < 0.006$) reduction is observed in the percentage of time that subjects in the intervention group spend being subjected to ergonomic risks in the high-risk range when RULA is used to conduct the postural ergonomic assessment, although a significant reduction is not observed when REBA is applied (p = 0.239 and p = 0.248 for high and very high risk levels, respectively). Meanwhile, the Welch's t-test reveals that there is a significant difference between the intervention and control group in terms of the time spent in the RULA high risk level (p = 0.002), though not in terms of the time spent in the REBA high (p = 0.239) and very high (p = 0.248) risk levels. This finding indicates that the proposed method successfully reduces the time spent in the high-risk range in RULA, thereby confirming the study hypothesis with respect to RULA assessments.

The main contributions of this study are the introduction of a method for real-time automated ergonomic risk assessment enabled by the integration of VR simulation and a MOCAP system and the demonstration of its application in a pre-test/post-test research experiment. The application of the proposed method provides an empirical evaluation of the impact of real-time postural ergonomic assessment incorporating postural recommendations in reducing subject's exposure to ergonomically hazardous postures, which is one of the research gaps identified in the existing literature.

6.7. Acknowledgments

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CHAPTER 7: CONCLUSIONS

7.1. Research Summary

Workers in construction manufacturing facilities are often exposed to repetitive motion and awkward body postures that are associated with the risk of developing work-related musculoskeletal disorders (WMSDs), despite the use of automated equipment on production lines. WMSDs are associated with high absenteeism, high injury rates, early retirement, and decreasing productivity on production lines. An investigation of the physical demands that workstations impose on workers' bodies and the provision of preventive measurements such as including ergonomics recommendations during training sessions is thus required in order to reduce the exposure of workers to these risks. In this context, the emphasis of this research is primarily on workstations at construction manufacturing facilities, in particular on developing VR-based simulation frameworks to provide (1) robust ergonomic assessments of tasks performed in construction manufacturing production lines, (2) timely ergonomic risk assessment of proposed design solutions for workstations designed for construction manufacturing facilities, and (3) real-time ergonomic risk assessment and postural recommendations during training on construction manufacturing tasks (with the aim of boosting worker awareness of ergonomically hazardous postures). The proposed frameworks rely on the body motion information acquired through traditional observation (Chapters 3 and 4) and direct physiological measurements (Chapters 5 and 6) for conducting the postural ergonomic risk analysis. In addition, questionnaire responses are analyzed to acquire subjects' perceptions of the task and of the VR simulation itself (Chapters 4, 5, and 6), while subjects' heart and respiratory rates are used to verify the physical workload of the task under study (Chapter 6).

In the first method (Chapters 3 and 4), a gap is identified in regard to deploying VR technology to evaluate workers' body motions in construction manufacturing tasks for the purpose of assessing ergonomic risks. To fill this gap, a VR-based method for ergonomic risk assessment relying on traditional observation is proposed that advances the use of VR for postural ergonomic analysis. A within-subject design research experiment is conducted with 13 participants, leading to the conclusion that VR is applicable to ergonomic risk assessments of tasks similar to the operational task explored in the research experiment conducted. The results of the application of this method indicate that a MOCAP system can be used to improve the accuracy of the calculations of Rapid Upper Limb Assessment (RULA) and Rapid Entire Body Assessment (REBA) risk scores. This recommendation is incorporated to the subsequent VR-based frameworks proposed in this research.

In the second method (Chapter 5), the need for a method in which robust ergonomic analysis can be performed in a laboratory setting during the workstation design stage in consideration of multiple aspects of ergonomics—e.g., motion, reachability of elements, and users' perceptions of the mental and physical workload of the task using the NASA Task Load Index (NASA-TLX)—is identified. In this context, a VR–MOCAP-enabled ergonomic risk assessment method is proposed that mimics and anticipates the body motions required for the completion of a given task such that ergonomic risks can be identified and mitigated at the workstation design stage. A practical application of the proposed method, in which 5 subjects complete the same task in both a physical prototype and a VR environment, is presented to demonstrate the feasibility of implementing the proposed method. The results demonstrate that the proposed method can successfully simulate therbligs of reaching and positioning.

The results obtained through the application of the VR–MOCAP-enabled ergonomic risk assessment method provide a solid foundation for the subsequent method proposed in this research, the SmartVRErgo method, which generates real-time postural recommendations during training on construction manufacturing tasks through VR simulation integrated with a MOCAP system (Chapter 6). For this purpose, RULA and REBA are used to evaluate postural ergonomic risks in real time. In addition, heart and respiratory rates are collected for the purpose of physical fatigue analysis and task workload analysis, and a questionnaire is administered to solicit feedback on subjects' perceptions of the VR simulation, and particularly the task's physical and mental workload (again using the NASA-TLX method). By conducting pre-test/post-test experimental research with 37 subjects, in which the proposed method is applied as the intervention in the experiment, the effectiveness of ergonomics training is verified through empirical evidence.

7.2. Research Contributions

This research proposes frameworks for using VR to simulate and analyze human factors, such as body motions and physiological measurements (i.e., heart and respiratory rates), associated with construction manufacturing tasks. The expected benefits of implementing the VR-based simulation frameworks proposed herein are numerous in that it (1) facilitates the simulation of entire tasks, production lines, etc.; (2) allows for the acquisition of body motion data within a controlled environment, thereby reducing the incidence of work interruptions; (3) provides proactive ergonomic analysis based on multiple ergonomics factors (i.e., body posture, heart and respiratory rates, reachability of elements, and subject's perception); (4) evaluates design options based on real motion data and thus reduces the reliance on physical prototypes for workstation design development; and (5) provides real-time ergonomic risk assessment and postural ergonomics recommendations during training on construction manufacturing tasks. The primary research contributions of this work are summarized below:

- The research described herein identifies the key challenges and issues inherent in the application of VR technologies to ergonomic analysis, thereby aiding in the development of future ergonomics-related VR studies targeting not only construction manufacturing but other research domains.

- The implementation of the proposed VR-based frameworks for ergonomic risk assessment provides an updated comparison of ergonomic risk assessments based on the observation of tasks conducted in both real and VR environments (Chapter 4 and 5), thereby verifying the effectiveness of the use of VR technologies to conduct ergonomic risk analysis of manufacturing tasks in the construction industry. Based on this updated comparison, it is verified that the proposed frameworks yield more accurate results when RULA, rather than REBA, is used as the assessment method.

- The proposed VR–MOCAP-enabled ergonomic risk assessment method, which enables semi-automated and proactive evaluation of ergonomic risks based on real motion data collected in a laboratory setting, can assist in analyzing workstation design options by identifying and mitigating ergonomic risks early in the workstation design stage. In addition to assessing postural ergonomic risks, this method provides holistic ergonomic analysis that combines objective (i.e., REBA and RULA scores, joint angles, and reachability analysis) and subjective criteria (i.e., questionnaire responses).

- The proposed SmartVRErgo method, which assesses postural ergonomic risks in real time and provides ergonomics recommendation based on subject's body motions during training on construction manufacturing tasks, can identify and prevent the worker behaviours associated with ergonomic risks in the high-risk range, thus limiting exposure of workers to the ergonomic risks associated with the development of WMSDs.

- The application of the proposed SmartVRErgo provides an empirical evaluation of the effectiveness of ergonomics training based on real-time ergonomic assessment integrated with postural recommendation in reducing the exposure of subjects to ergonomic risks in the high-risk range.

7.3. Limitations and Future Research

The following are proposed as avenues of future research to improve the performance of the proposed frameworks and address some of the limitations of this research:

- The proposed VR-based simulation frameworks support ergonomic analysis of construction manufacturing tasks in which the weight of the elements handled manually does not exceed 2 kg, which covers the majority of tasks completed in semi-automated workstations in construction manufacturing facilities. Further investigation is required to adapt the proposed frameworks to the analysis of manual handling tasks involving elements weighing more than 2 kg (and thus incorporating forceful exertion factors in the analysis). In this context, the use of mixed reality is recommended as a future research direction.

- Considering that the VR–MOCAP-enabled ergonomic risk assessment method is applied in a research experiment with five participants, the statistical power of analysis of its implementation is limited. For this reason, expanding the number of participants in future studies is encouraged to further demonstrate the validity of this method.

- The proposed SmartVRErgo can significantly reduce the percentage of time spent in ergonomic risks in the high-risk range when RULA is deployed as a postural assessment method. However, its application to more physically demanding tasks is required in order to verify whether similar results are achieved with respect to heart and respiratory rates.

- Although both RULA and REBA are deployed for ergonomic risk assessment of body postures in this research, RULA is found to yield more accurate results than REBA when comparing the risk assessment of a given task in both real and VR environments. This finding indicates that further investigation of the application of REBA for VR-based ergonomic risk assessments is required.

- The investigation of elemental motions observed in construction manufacturing tasks (completed in both real and VR environment as the basis for identifying acceptable sway magnitudes for the flexion, axial, and side rotation angles) is encouraged as a way of tailoring the RULA and REBA calculations to VR-based ergonomic risk assessment.

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APPENDIX A

The questionnaire designed in Subsection 4.3.3 of Chapter 4: is presented in Figure A.1.

Feedback on VR Application for Ergonomic Risk Assessment

As per the INFORMATION LETTER and CONSENT FORM signed, you have consented to participate in this research experiment. You are under no obligation to participate in this study as your participation is completely voluntary; you will not receive any financial benefit for participating in this study; your participation will not result in any financial costs for you; you retain the right not to answer specific questions, even if participating in the study; you have the right to end your participation in the study at any time. Withdrawal of corresponding collected data from the study can be accommodated if requested within 2 weeks following signing of this consent form. To withdraw from the study, please contact me by email (rdbarkokebas@ualberta.ca) or phone (780-995-9207) within two weeks of the date on your signed consent form.

The original consent form containing additional information about this research is available at the following link: https://1drv.ms/w/s!At4M2NMdP7hzjX6MD98foaEm0wVB?e=C4DgaQ

The respondent's email (**null**) was recorded on submission of this form.

1. Email *

____

Background of participants

Please answer these questions about yourself.

2. 1. To which gender identity do you most identify?

Mark only one oval.

- ◯ Female
- ◯ Male
- ◯ Transgender Female
- ◯ Transgender Male
- ◯ Gender Variant/Non-Conforming
- ◯ Prefer not to disclose
- ◯ Other: ______________________________

3. 2. What is your age?

____

4. 3. What is your height?

____

5. 4. Do you wear corrective glasses?

Mark only one oval.

- ( ) Yes
- ( ) No

6. 5. What is your education level?

Mark only one oval.

- ( ) Bachelor (pursuing or completed)
- ( ) Graduate (pursuing or completed)

7. 6. What is your educational background?

Mark only one oval.

- ( ) Engineering
- ( ) Architecture
- ( ) Other

8. 7. Have you had musculoskeletal injuries before?

Mark only one oval.

- ( ) Yes
- ( ) No

9. 7.1. If yes, how recently?

____

10. 7.2. If yes, please briefly describe your injury.

____
____
____
____
____

11. 8. Have you had experience with virtual reality (VR) technology before?

Mark only one oval.

- ◯ Yes
- ◯ No

12. 8.1. If yes, how recently?

____

13. 8.2. If yes, how often do you use VR or other gaming technology?

____

Usability of VR

Please select the option that best reflect your opinion.

14. 1. In general, I felt that the VR environment is a close representation of reality.

Mark only one oval.

	1	2	3	4	5	
Strongly disagree	◯	◯	◯	◯	◯	Strongly agree

15. 2. I felt comfortable wearing the VR headset.

Mark only one oval.

	1	2	3	4	5	
Strongly disagree	◯	◯	◯	◯	◯	Strongly agree

16. 3. I felt safe using VR.

Mark only one oval.

	1	2	3	4	5	
Strongly disagree	◯	◯	◯	◯	◯	Strongly agree

17. 4. I felt immersed in the virtual environment while experimenting with the VR application.

Mark only one oval.

	1	2	3	4	5	
Strongly disagree	◯	◯	◯	◯	◯	Strongly agree

18. 5. I felt engaged while experimenting with the VR application.

Mark only one oval.

	1	2	3	4	5	
Strongly disagree	◯	◯	◯	◯	◯	Strongly agree

19. 6. The wire from the headset did not bother me during the experiment.

Mark only one oval.

	1	2	3	4	5	
Strongly disagree	◯	◯	◯	◯	◯	Strongly agree

20. 7. The VR application is intuitive.

Mark only one oval.

	1	2	3	4	5	
Strongly disagree	◯	◯	◯	◯	◯	Strongly agree

21. 8. The interactions added to the VR experiment are of a high level of quality.

Mark only one oval.

	1	2	3	4	5	
Strongly disagree	◯	◯	◯	◯	◯	Strongly agree

22. 9. The tag showing the progress status was helpful.

Mark only one oval.

	1	2	3	4	5	
Strongly disagree	◯	◯	◯	◯	◯	Strongly agree

Task simulation

Please select the option that best reflect your opinion.

23. 1. The tasks were similar to real-world tasks.

Mark only one oval.

	1	2	3	4	5	
Strongly disagree	◯	◯	◯	◯	◯	Strongly agree

24. 2. I could see all the tools and pieces of equipment required to complete the task.

Mark only one oval.

	1	2	3	4	5	
Strongly disagree	◯	◯	◯	◯	◯	Strongly agree

25. 3. I was able to pick up tools and equipment easily.

Mark only one oval.

	1	2	3	4	5	
Strongly disagree	◯	◯	◯	◯	◯	Strongly agree

26. 4. A had a good understanding of the task being performed.

Mark only one oval.

	1	2	3	4	5	
Strongly disagree	◯	◯	◯	◯	◯	Strongly agree

27. 5. I was satisfied with my performance of the task.

Mark only one oval.

	1	2	3	4	5	
Strongly disagree	◯	◯	◯	◯	◯	Strongly agree

28. 6. The tools had a similar size to those in the real-world.

Mark only one oval.

	1	2	3	4	5	
Strongly disagree	◯	◯	◯	◯	◯	Strongly agree

29. 7. The tools were aesthetically similar to those in the real-world.

Mark only one oval.

	1	2	3	4	5	
Strongly disagree	◯	◯	◯	◯	◯	Strongly agree

30. 8. I felt that my body movements during the VR experiment were similar to those in the real-world.

Mark only one oval.

	1	2	3	4	5	
Strongly disagree	⬭	⬭	⬭	⬭	⬭	Strongly agree

Additional feedback

Please use this section if you would like to provide additional feedback.

31. Comments

Figure A.1: Questionnaire design in Subsection 4.3.3.

APPENDIX B

The questionnaire included in the methods proposed in Chapter 5: and Chapter 6: is detailed in Figure B.1.

Feedback on VR Application for Ergonomic Risk Assessment

As per the INFORMATION LETTER and CONSENT FORM signed, you have consented to participate in this research experiment. You are under no obligation to participate in this study as your participation is completely voluntary; you will not receive any financial benefit for participating in this study; your participation will not result in any financial costs for you; you retain the right not to answer specific questions, even if participating in the study; you have the right to end your participation in the study at any time. Withdrawal of corresponding collected data from the study can be accommodated if requested within 2 weeks following signing of this consent form. To withdraw from the study, please contact me by email (rdbarkokebas@ualberta.ca) or phone (780-995-9207) within two weeks of the date on your signed consent form.

The original consent form containing additional information about this research is available at the following link: https://1drv.ms/w/s!At4M2NMdP7hzjX6MD98foaEm0wVB?e=C4DgaQ

* Required

Background of participants

Please answer these questions about yourself.

1. 1. What is your height? *

   ____

2. 2. Did you wear corrective glasses during the experiment? *

   Mark only one oval.

   ◯ Yes

   ◯ No

3. 3. Have you had musculoskeletal injuries before?

   Mark only one oval.

   ◯ Yes

   ◯ No

4. 3.1. If yes, how recently?

____

5. 3.2. If yes, please briefly describe your injury.

6. 4. Have you had experience with virtual reality (VR) technology before?

Mark only one oval.

- ( ) Yes
- ( ) No

7. 4.1. If yes, how often do you use VR or other gaming technology?

____

Perceived comfort (application of the NASA Task Load Index questionnaire)

Please select the option that best reflect your opinion.

8. How mentally demanded is the task?

Mark only one oval.

	1	2	3	4	5	6	7	
Very low	( )	( )	( )	( )	( )	( )	( )	Very high

9. How physically demanded is the task?

Mark only one oval.

	1	2	3	4	5	6	7	
Very low	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Very high

10. How hurried or rushed is the pace of the task?

Mark only one oval.

	1	2	3	4	5	6	7	
Very low	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Very high

11. How successful to you think you were in accomplishing the task?

Mark only one oval.

	1	2	3	4	5	6	7	
Very low	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Very high

12. How hard did you have to work (mentally and physically) to accomplish your level of performance?

Mark only one oval.

	1	2	3	4	5	6	7	
Very low	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Very high

13. How insecure, discouraged, irritated, stressed, and annoyed were you during the task?

Mark only one oval.

	1	2	3	4	5	6	7	
Very low	◯	◯	◯	◯	◯	◯	◯	Very high

Usability of VR

Please select the option that best reflect your opinion.

14. 1. In general, I felt that the VR environment is a close representation of reality.

Mark only one oval.

	1	2	3	4	5	
Strongly disagree	◯	◯	◯	◯	◯	Strongly agree

15. 2. I felt safe using VR.

Mark only one oval.

	1	2	3	4	5	
Strongly disagree	◯	◯	◯	◯	◯	Strongly agree

16. 3. I felt immersed in the virtual environment while experimenting with the VR application.

Mark only one oval.

	1	2	3	4	5	
Strongly disagree	◯	◯	◯	◯	◯	Strongly agree

17. 4. I felt engaged while experimenting with the VR application.

Mark only one oval.

	1	2	3	4	5	
Strongly disagree	◯	◯	◯	◯	◯	Strongly agree

18. 5. The VR application is intuitive.

Mark only one oval.

	1	2	3	4	5	
Strongly disagree	◯	◯	◯	◯	◯	Strongly agree

Task simulation

Please select the option that best reflect your opinion.

19. 1. The tasks were similar to real-world tasks.

Mark only one oval.

	1	2	3	4	5	
Strongly disagree	◯	◯	◯	◯	◯	Strongly agree

20. 2. I could see all the tools and pieces of equipment required to complete the task.

Mark only one oval.

	1	2	3	4	5	
Strongly disagree	◯	◯	◯	◯	◯	Strongly agree

21. 3. I was able to pick up tools and equipment easily.

Mark only one oval.

	1	2	3	4	5	
Strongly disagree	◯	◯	◯	◯	◯	Strongly agree

22. 4. A had a good understanding of the task being performed.

Mark only one oval.

	1	2	3	4	5	
Strongly disagree	◯	◯	◯	◯	◯	Strongly agree

23. 5. I was satisfied with my performance of the task.

Mark only one oval.

	1	2	3	4	5	
Strongly disagree	◯	◯	◯	◯	◯	Strongly agree

24. 6. The tools were aesthetically similar to those in the real-world.

Mark only one oval.

	1	2	3	4	5	
Strongly disagree	◯	◯	◯	◯	◯	Strongly agree

25. 7. I felt that my body movements during the VR experiment were similar to those in the real-world.

Mark only one oval.

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

Additional feedback

Please use this section if you would like to provide additional feedback.

26. Comments

Figure B.1: Questionnaire deployed in the methods proposed in Chapter 5: and Chapter 6:.