DEVELOPING A WEARABLE TECHNOLOGY PROTOCOL FOR FATIGUE RISK REDUCTION ON CONSTRUCTION SITES

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DEDICATION

Firstly, this research work is dedicated to my wife, Boikokobetso Mtetwa for her love, support, and encouragement.

Secondly, I dedicate this dissertation to my mother, Nomusa Mtetwa for her love, inspiration, and guidance.

Thirdly, I would like to dedicate this work to my mentors, Marius & Nozipho Swart and Sahluko & Lorraine Sithole.

Fourthly, this dissertation is dedicated to my nieces, Siphosomusa Mtetwa, Mpilonhle Mtetwa, Anande Ngcobo, Lethiwe Mtetwa, Liyanatibusiso Kubayi, and Siphosethu Gwebu, Nolwethu Gwebu, Okuhle Gwebu.

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I dedicate this work to my brothers Phathizwe Gwebu, Muzi Gwebu, and Bheki Gwebu.

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LIST OF PUBLICATIONS

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2. Mtetwa, S.I., Mollo, L.G. and Emuze, F.A. (2024). Wearable technology to reduce fatigue risks for construction workers: a scoping review. *Proceedings of the WABER SuDBE Conference 2024*, (pp. 1219-1232). 30-31 July 2024. University of the Witwatersrand. Johannesburg, South Africa. ISBN: 978-0-07961-6032-4.

ABSTRACT

Construction personnel operate in an industry that is known to inflict all kinds of psychosocial harm because of poor work environments, and excessive working hours. This reality perpetuates physical and mental fatigue risks for workers on construction sites. This study is aimed at developing a wearable technology (WT) protocol to reduce fatigue risk factors on construction sites. To achieve this aim, this study used an exploratory research design. The data were collected using mixed methods research. A multiple case study design was employed to collect qualitative data through semi-structured interviews from three (3) case projects in Bloemfontein, Free State province of South Africa. The quantitative data were collected from one hundred and sixteen (116) construction personnel in South Africa's Free State province using survey questionnaires. The qualitative data were analysed by means of thematic and cross-case analysis methods, and the quantitative data were analysed through descriptive analysis method. The findings of this study resulted in the development of a WT protocol that would help reduce fatigue risk factors on construction sites. The WT protocol followed a six-step synergistic procedure to help select suitable WT, monitor fatigue risks, aggregate and analyse fatigue data, communicate fatigue results, and consider compliance and usability of fatigue data to reduce construction workers' fatigue risks. The study presented various limitations including the proposed WT protocol not being tested on a live project to monitor construction personnel's fatigue risks. Therefore, future research should test and validate the effectiveness of the proposed WT protocol to investigate workers' fatigue risks on a live construction project.

Keywords: Construction personnel, construction work environment, fatigue, health and safety, wearable technology

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THE DEFINITION OF KEY TERMS

Chronic diseases or ailments	The World Health Organization (WHO) defines a chronic disease as an ailment of long duration which progresses slowly and is non-communicable; that means it can not be passed from person to person (WHO, 2014; WHO, 2022).
Construction personnel	Refers to construction stakeholders involved in a particular project. These stakeholders include professionals, managers, artisans, plant operators, and general workers (Leung et al., 2015).
Construction Regulations	The Construction Regulations of 2014 is aimed at improving building standards and safety in the construction industry. In South Africa, the Construction Regulations of 2014 addressed common hazards faced by construction workers (Emuze, 2020) as well as health and safety performance in construction projects (Malindi and Smallwood, 2018).
Fatigue	Refers to the reduction in the transient performance of the muscles to apply optimal force after undergoing a physical activity. It is not a condition but a symptom as it develops moderately in steps over time for works that do not demand continued employment of maximum possible force (Sharma and Sethi, 2022).
Health	Health is a multifaceted concept encompassing emotional, spiritual, environmental, mental, physical, and social aspects, not merely the absence of disease (Skiadas and Skiadas, 2020). It deals with physical, biologic, psychological, and social stress (WHO, 2014).
Health and Safety	Laws and procedures designed to avoid accidents, injuries, and fatalities in the workplace, thus, ensuring the wellbeing of workers on-site (Hughes & Ferrett, 2011).
Job Site	A physical site where labour, particularly building activity, is performed (Nguyen et al., 2024).

Latent Health Effects	Effects that occur when an exposure is followed by a period before a specific reaction develops that is health related (Shan et al., 2017).
Mental Health	Mental health is a state of well-being that encompass cognitive, behavioral, emotional, social, and psychological aspects (Richardson, 2020). It involves ones ability of manage stress, anxiety, and depression while maintaining productive daily activities (Richardson, 2020).
Occupational Health and Safety Act	A law that requires the employer to create and maintain, as far as is practically feasible, a safe and health working environment for the employees (Michaels & Wagner, 2020).
OHSA 85 of 1993	The Occupational Health and Safety Act 85 of 1993 (OHSA) is an important piece of legislation in South Africa aimed at ensuring a safe working environment for employees. The Act places the responsibilities of maintaining workplace safety and health on the employers (Machabe and Indermun, 2013).
Occupational Safety and Health Administration	The Department of Labour's public health agency. OSHA, established in 1970 by the Occupational Safety and Health Act, is responsible for ensuring that businesses provide their employees with a working environment free of known health and safety concerns (Michaels & Wagner, 2020).
Personnel	Persons who work for a firm, an organisation, or the armed forces (Zheng, 2021).
Physical Health	Physical health is a multifaceted concept that encompass more than just the absence of disease. It involves maintaining a quality of life that allows for daily activities without undue fatigue or stress (Donoghue, 2018).
Poor Health	A situation in which a person is unable to fulfil what is expected of them physically, psychologically, or socially (Toppr, 2022; WHO, 2022).

Private Construction Projects	Construction projects held by a private individual or corporation (Leung et al., 2015).
Protocol	A system of rules that can be used by construction personnel to structure a timely fatigue monitoring and control procedure on a construction site (Mayhew, 2019).
Public Construction Projects	Construction projects that are owned by the government.
Real Health	A full condition of physical, mental, and social well-being, as opposed to the absence of sickness or infirmity (WHO, 2022).
Real Time	The exact time when a process or event happens (Lee et al., 2018).
Safety	is a critical aspect of organizational management, encompassing strategies to ensure employee health, welfare, and protection from hazards (Sulegam, 2019).
Wearable Sensing Devices	Are any electronic equipment or product that may be worn by the user to deliver a specific function (Awolusi et al., 2018).
Wearable technology	A type of electronic gadget that may be worn as fashion accessory or integrated in clothing. The devices are hands-free gadgets with practical applications that are controlled by microprocessors and have the capacity to send and receive data through the internet (Awolusi et al., 2019).
Wellbeing	Wellbeing is a complex concept encompassing positive feelings and the realization of one's full potential (Simons and Baldwin, 2021).
Workers	Persons who conduct construction work or operate in a specific manner on site (Nguyen et al., 2024).
Workmanship	The level of ability with which a product is manufactured, or a job is completed (Nguyen et al., 2024).

LIST OF ABBREVIATIONS & ACRONYMS

BIM	Building Information Modelling
CDC	Centers for Disease Control and Prevention
CSC	Construction Safety Council
CP	Construction personnel
CR	Construction Regulations
DEL	Department of Employment and Labour
DoL	Department of Labour
ERPS	Enterprise Resource Planning Systems
FEM	Federated Employers Mutual Assurance Company
FRMS	Fatigue Risk Management Systems
GDP	Gross Domestic Product
GPS	Global Positioning System
H&S	Health and Safety
HSE	Health and Safety Executive
HSW	Health, Safety, and Well-being
HSPH	Harvard School of Public Health
ILO	International Labour Organizations
IS	Information Systems
IT	Information Technology
NHBRC	National Home Builders Registration Council
OHS	Occupational Health and Safety
OHSA	Occupational Health and Safety Act
OSA	Obstructive Sleep Apnoea
OSHA	Occupational Safety and Health Administration
PPE	Personal Protective Equipment
RP	Research Participant
SA	South Africa

SDG	Third Sustainable Development Goal
UN	United Nations
USA	United States of America
USD	Undiagnosed Sleep Disorders
WHO	World Health Organisation
WSD	Wearable Sensing Devices
WT	Wearable Technology

CHAPTER 1: THE BACKGROUND OF THE STUDY

1.1. Introduction

The construction industry is infamous for its drastic contribution to health and safety (H&S) problems emanating from each project implementation (Amoah & Simpeh, 2021). It is ranked among the most hazardous sectors worldwide (ILO, 2022). The International Labour Organization (ILO) reported that construction workers in developed contries have a 3 to 4 times likelihood of encountering fatal accidents with a 3 to 6 times probability in less developed countries (ILO, 2014). For example, in South Africa, the construction industry is regarded as one of the highest contributors to injuries, ill-health, and fatalities (Ikuabe et al., 2021). The Department of Employment and Labour (DEL) of the Republic of South Africa also highlighted that the construction industry remains in the top four high-risk sectors in the country with approximately two deaths occurring each week (DEL, 2024). In 2023, The Federated Employers Mutual Assurance Company (RF) (Pty) Ltd (FEM) reported 6157 accidents including 48 deaths and 581 permanent disabilities based on the insurance claims made by construction industry employers in 2022 (FEM, 2023). For this reason, optimizing worker health, safety, and wellbeing (HSW) remains a significant factor in construction (Nnaji et al., 2021).

Construction undertakings are labour-intensive and effort demanding throughout projects' execution process (Sharma & Sethi, 2022). This reality presents a high probability of fatigue, injuries, and fatalities among people in construction. Fatigue is regarded as a major contributor to numerous construction accidents on-site (Aryal et al., 2017). Construction projects expose site personnel to lifting enormous workloads, working extra time than expected, and executing demanding tasks that cause physical fatigue inevitable (Zhang, 2019; Sharma & Sethi, 2022). Since fatigue is not a condition but a symptom of continued lifting, bending, or twisting of maximum load or force, necessary technological implements are required to determine the cause of fatigue (Sharma & Sethi, 2022). Fatigue can sometimes be triggered by risk factors related to musculoskeletal disorders emanating from construction activities (Patel et al., 2021). It can also emanate from stressful circumstances, and sleeplessness (Chan et al., 2019). Therefore, wearable technology (WT) is needed to monitor the HSW of construction personnel to minimise the likelihood of fatigue (Okhifun, 2020).

In 2013, researchers at the Harvard School of Public Health (HSPH) published a study titled "Construction Workers Struggle With a High Prevalence of Mental Distress, and This Is Associated With Their Pain and Injuries" (Jacobsen et al., 2013). This investigation underpinned the difficulties that construction personnel undergo which in turn affect their mental health and sleep (Jacobsen et al., 2013). The study revealed that construction workers are habitually stressed by work-related injuries and pain, leading to more injuries and mental health issues such as depression, anxiety, and even suicide (Jacobsen et al., 2013). Dwyer (2013) supported the findings by suggesting that the construction workforce is routinely stressed by work-related pain and injuries. Turner and Lingard

(2020) also argued that factors such as depression, anxiety, and stress affect workers' ability to undertake construction tasks. Furthermore, a study by Chan et al. (2019) postulated that site personnel suffer mental distress prompting their cognitive fatigue (Chan et al., 2019). Therefore, in the absence of help, construction personnel find themselves at risk of suffering even more injuries and mental health problems such as fatigue. These challenges necessitate the adoption of advanced H&S tools in construction projects to reduce workers' fatigue risks (Collins, 2019).

The health challenges in construction have received minimal attention (Mwanaumo & Thwala, 2012; Moyo et al., 2021). Instead, they have been aligned with the anticipation, recognition, evaluation and control of occupational health hazards since workers' safety has been at the forefront (Mwanaumo & Thwala, 2012; Ahn et al., 2019; Moyo et al., 2021). The health hazards encompass chemical, biological, physical, and noise exposure perpetrated by construction undertakings, although some workers occassionally get to construction sites already fatigued (Health and Safety Executive, 2018; Ahn et al., 2019). Therefore, technological advancements such as wearable technology are required to monitor fatigue risks in construction (Ahn et al., 2019; Musarat et al., 2022).

WTs are gadgets that may be worn as fashion accessories or integrated in clothing items (Ahn et al., 2019). The devices are hands-free gadgets with practical applications that are controlled by microprocessors and have the capacity to send and receive data through the internet (Awolusi et al., 2019). These can be further described as any electronic equipment that may be worn by people on-site to provide the analysis of health conditions such as fatigue, stress, etc. (Moyo et al., 2021; Nnaji et al., 2021). Wearable technology has recently advanced, making it possible to gather and convert H&S data timeously (Ahn et al., 2019; Nnaji et al., 2021; Musarat et al., 2022). As such, this study argues that a WT protocol would help monitor site personnel's fatigue risks through an efficient collection and analysis of real-time data.

1.2. The Problem Statement

Fatigue poses serious threats to health, safety, and well-being of construction personnel (Zong et al., 2024). The labour-intensive nature of construction work environment, coupled with cognitive strain and exposure to environmental stressors, often results in reduced performance, alertness, and increased likelihood of accidents on site (Howe et al., 2024). Although systems such as fatigue risk management systems (FRMS) have had a positive safety outcome, current workplace protocols lack effective measures to proactively monitor and manage fatigue (Sprajcer et al., 2022). Therefore, there is a need for a wearable technology protocol that integrates real-time monitoring, data analysis, and personalized interventions to reduce fatigue and optimize worker performance in construction environments (Rane et al., 2023).

Fatigue is a serious symptom that is difficult to diagnose as it stems from factors such as obstructive sleep apnoea, stress, excessive lifting, bending, twisting, etc. (Zhang, 2019; Goodson, 2023). A study conducted by the International Labour Organization (ILO) showed that approximately 2.78

million workers die annually, while 374 million workers encounter nonfatal injuries in the workplace globally (International Labour Organization, 2019; Patel et al., 2021). The research exposed that the workdays lost due to accidents and amount spent on injuries accumulates to 4% of each country's GDP in both developing and developed countries ((International Labour Organization, 2019). This scathing rate of productivity time loss due to accidents, injuries, fatigue-related risks is detrimental to the schedule and total cost of the project, thus, tarnishing the reputation of construction companies (Wolf et al., 2018; Patel et al., 2021). Therefore, optimising construction personnel's HSW by reducing the rate of physical and cognitive fatigue using WT on sites is necessary (Patel et al., 2021; Rane et al., 2023).

1.3. Research Question and Sub-questions

The main research question of this study asked, "How can a wearable technology protocol help inform about fatigue risk factors on construction sites?" To respond to this research question, the following sub-questions were formulated:

1.3.1. Sub-question 1

What are the best practices for using wearable technology to leverage data metrics to investigate fatigue risk factors?

1.3.2. Sub-question 2

How can wearable technology be used to evolve early fatigue interventions to help construction personnel?

1.3.3. Sub-question 3

How would wearable technology inform about fatigue risk factors for the work environment and methods of work?

1.3.4. Sub-question 4

How would wearable technology inform about fatigue risk factors for plant and equipment operation?

1.3.5. Sub-question 5

How will the development of a wearable technology protocol help reduce fatigue risk factors on construction sites?

1.4. Research Aims and Objectives

The aim of this study was to develop a wearable technology protocol that would help inform about fatigue risk factors on construction sites. Thus, the research objectives of the study include:

1.4.1. Objective 1

Identify the best practices of using wearable technology to leverage data metrics to investigate fatigue risk factors.

1.4.2. Objective 2

Describe how to use wearable technology to evolve early fatigue interventions to help construction personnel.

1.4.3. Objective 3

Evaluate how wearable technology would inform about fatigue risk factors for the work environment and methods of work.

1.4.4. Objective 4

Evaluate how wearable technology would inform about fatigue risk factors for plant and equipment operation.

1.4.5. Objective 5

Develop a wearable technology protocol that would help reduce fatigue risk factors on construction sites.

1.5. Delimitations of the Study

The scope of the study had innumerable limitations which were within the researcher's control. Some of these limitations included:

- Only three (3) case studies were used for qualitative data due to logistical constrains.
- Participants were sampled within Free State province of South Africa to achieve diverse perspectives.
- The study investigated construction personnel within construction and consulting firms based in Free State province of South Africa.

1.6. Limitations of the Study

The research process also encounters some limitations beyond the researcher's control. These included:

- The sampled construction firms and construction personnel had no prior knowledge of WT and its relevance to the construction industry. This made interviews to take longer than anticipated.
- Most interviews and survey questionnaire data were collected from site in the season where intense winds and dust exist. This made it difficult to conduct interviews as the winds would blow the interview instruments and cause loud noises in the recording. That is because, the site did not have covering or places where these instruments could be administered since the project involved site establishment, excavations, underground plumbing, levelling, and routine road maintenance.

- A few construction personnel did not want to participate in interviews or complete survey questionnaires.
- Many interview appointments and site visits were either cancelled or delayed since the researcher was not allowed to be on-site without the H&S manager's supervision.

1.7. The Assumptions

The reality facing the construction industry is poor workers' HSW in project endeavours, leading to accidents, injuries, and fatalities. This reality has tarnished the reputation of the construction industry, despite its contribution to the world's gross domestic product (GDP); improving employment rates, creating better infrastructure, enhancing living standards, contributing to social benefits, etc. Some of the assumptions of this study include the following:

- The construction designs and plans are not well aligned with Construction Regulations 2014 to minimise HSW challenges.
- Fatigue is a symptom of continuous lifting, bending, twisting, overexertion, and stress.
- The rate of construction site accidents continues to escalate due to many undiagnosed health issues including fatigue.
- The use of technology could help inform about fatigue and other latent health factors affecting construction personnel on construction sites.

1.8. Research Design and Methodology Summary

This section presents the methodological choice and approach that was followed in this study for data collection and analysis.

1.8.1. Design

This study developed a WT protocol to detect construction personnel's fatigue risk factors. The purpose of this study aligned to the use of an exploratory research design. Exploratory research is suitable when a lot is unknown about a phenomenon or its problem has not been clearly defined (Saunders et al., 2019). It does not aim to provide the final and conclusive answers to the research questions, but merely explores the research topic in depth. As a result, this study adopted an exploratory research design to explore the research objectives further.

1.8.2. Sampling

A mixed methods research method was adopted to collect qualitative and quantitative data for this study. The qualitative research data were collected using a case study strategy. Three (3) case studies were used including residential, industrial, and routine road maintenance case projects. A non-probability sampling technique through a heterogenous purposive sampling was adopted to select interviewees. The Interviewees were forty-eight (48) in total (e.g., residential case study = 27, Industrial case study = 9, and routine road maintenance case study = 12). The research sample encompassed tilers, TLB operators, tipper truck operator, bobcat operator, site supervisors or forepersons, health and safety officer, carpenter, painter, welder, roof carpenter, general workers, estate manager, quantity surveyors, cleaner, storeroom helper, plumbers, bricklayers, construction manager, broomer operator, smooth drum roller operators, diesel truck operator, steel fixing specialist, shuttering specialist, grader operator, driver, brush cutter operators, and director or supervisor across three case projects in the Free State province of South Africa. This sample was purposively selected because of diverse expertise and experience. The quantitative research data were collected using survey questionnaires. A probability sampling technique through simple random sampling was used to obtain statistical data from 116 construction personnel in the Free State province of South Africa (McCombes, 2019). The research sample included civil engineers, site forepersons, tilers, TLB operators, tipper truck operator, bobcat operator, site supervisors, health and safety officer, carpenter, painter, welder, roof carpenter, general workers, estate manager, quantity surveyors, cleaner, storeroom helper, plumbers, bricklayers, construction managers, broomer operator, smooth drum roller operators, diesel truck operator, steel fixing specialist, shuttering specialist, grader operator, driver, brush cutter operators, director, construction project managers, healthand safety agents, architects around the Free State, South Africa.

1.8.3. Instrument design and data collection

This research adopted a mixed methods for data collection. The qualitative data of this study were collected using open-ended semi-structured interviews. The quantitative data were obtained through closed-ended survey questionnaires. The research instruments were administered in an ethical manner that protected the research participants (RPs) and academic integrity of the procedure.

1.8.4. Data analysis

The qualitative data were analysed using a thematic and cross-case analysis. The quantitative data was analysed using descriptive statistical analysis.

1.9. The Importance of the Study

Construction personnel are susceptible to fatigue due to occupational stressors such as risky labour, production constraints, quick and complicated decision-making, and the responsibility for others safety (Dwyer, 2013). They operate in an industry that is known to inflict additional psychosocial harm; transience, temporary work contracts, poor work environment, and excessive working hours which are perceived to pose similar harm as dust and noise to the health of people in construction (Sherratt, 2017). These harmful effects have unavoidably resulted in high levels of smoking, drinking, overeating, and drug usage by construction personnel. Which may be interpreted as symptoms of such cumulative workplace concerns, and further perpetrating various emotional harm and ailments thereof. This is a scathing diagnosis, and significant consideration is still being emplaced.

Therefore, the health and well-being of construction personnel are now as vital as safety, and the construction sector is making remarkable steps to address poor occupational and public health (Awolusi et al., 2020). However, given the intricacy of the linkages described above, a thorough analysis of construction personnel's health should be done because health concerns are complex and cannot be remedied by just using personal protective equipment (PPE). This reality necessitates engineering, and technological advancements to eliminate, substitute, and control the risk of fatigue on construction sites (Sherratt, 2017; Zhang, 2019). As such, the development of WT protocol remains a solution in assessing the HSW of construction personnel on job sites by properly measuring fatigue (Nnaji et al., 2021).

Although various WT experiments have been undertaken to understand the effectiveness of wearables on construction sites (Jebelli et al., 2018; Ahn et al., 2019), there is still a need for a WT protocol to reduce fatigue related risk factors on-sites. Many studies have explored physical fatigue as one of the elements within the study of ergonomics (Ni et al., 2022), leaving a huge gap of aligning safety, health, and wellbeing through the detection of mental fatigue (Tseng et al., 2021). Physical fatigue focuses on H&S, while mental fatigue engenders workers' wellbeing and health (Caldwell et al., 2019; Tseng et al., 2021; Ni et al., 2022; Sharma & Sethi, 2022). The development of a proper WT protocol is significant to control both physical and mental fatigue among construction personnel (Karg et al., 2014; Sharma & Sethi, 2022).

Fatigue is a difficult phenomenon to investigate. Technological aid including WT that can detect physiological signals and internal health such as heart rate, blood pressure, heat stress, etc. is required. Therefore, the significance of this study is centred around the development of a WT protocol that could help evolve fatigue risks interventions. This would ultimately help inform about construction workers' fatigue risks on site, resulting in improved workers' HSW in the workplace. The protocol would further assist in the development of the fatigue detection, analysis, and communication procedure to integrate H&S information of construction personnel on a single database. Thus, informing continuous HSW improvement and increased awareness of fatigue risk factors on construction undertakings.

1.10. Social Impact

This study aimed to address the following United Nations Sustainable Development Goals:

- **SDG 3 – Good Health and Wellbeing (Fei et al., 2021)**

The implementation of WT on-site would allow the detection of fatigue risk factors to inform the improvement of the HSW of workers during the construction process on-site.

- **SDG 8 – Decent Work and Economic Growth (Goubran, 2019)**

Improved work environment and methods would improve H&S; thus, enhancing productivity, minimizing expenditure on medical bills, and increasing the return on investment. This initiative would translate to good work conditions and better economic state for the workers, enterprise, and the country (e.g. GDP).

- **SDG 9 – Industry, Innovation, and Infrastructure (Ogunmakinde, Egbelakin & Sher, 2022)**

Promoting the use of WT in construction would increase the demand and necessitate the production of wearable devices. Furthermore, the development of WT protocol would influence how it is perceived by the industry stakeholders; thus, fostering innovation and increasing use.

1.11. Outline of the Dissertation

This dissertation was organised as follows:

Chapter 1: Background of the study

The first chapter introduced the focus of this research on the development of WT protocol to improve the HSW of workers in construction. This investigation was undertaken on multiple construction sites in Bloemfontein to determine the effectiveness of WT protocol in improving construction site personnel's HSW on the jobsite.

Chapter 2: The Literature Review

This chapter elaborated on how WT are often integrated into personal items. The chapter extensively explored WT and various technologies available for fatigue determination and workers' HSW improvement in construction. It further evaluated how wearables would inform redesigning the work environment, work methods, as well as plant and equipment to reduce fatigue risk factors on construction sites.

Chapter 3: Research Methodology

This chapter focused on the approaches that the researcher employed to carry out this study. The section provided sampling techniques and data collection mechanisms that aim to respond to the research questions and objectives.

Chapter 4: Results and Interpretations

This chapter discussed the results of the extensive monitoring and mapping of the research region. it explored how the WT protocol could be developed and used to analyse construction personnel's fatigue on job sites. The section outlaid the qualitative and quantitative information divulged from the construction sites thereof.

Chapter 5: Analysis and Discussion

This chapter expanded further on all the findings from the fourth chapter pursuant to the research objectives. The chapter also compared the findings to the literature to draw conclusions on the subject matter.

Chapter 6: Conclusions and recommendations

The final chapter consolidated the information derived from the findings and concluded based on the correlation with the research objectives. Furthermore, recommendations were made to prove the effectiveness of the WT protocol.

1.12. Chapter Summary

This chapter discussed the research background, problem statement, research questions, aim and objectives, assumptions, limitations and delimitations, significance of the study, and social impact. The chapter also presented a synopsis of the research structure. The following chapter presents a narrative review of relevant literature pursuant to wearable technology and fatigue in construction.

CHAPTER 2: LITERATURE REVIEW

2.1. Introduction

The purpose of this chapter is to present a review of existing literature relative to WT and fatigue. The chapter explored various types of WT, discussed fatigue and investigated its effects to the work environment, work methods, and plant and equipment. This chapter responded to four (4) research questions which focuses on various elements to which fatigue can be detected using wearables for real health and safety monitoring of construction personnel.

2.2. The nature of construction work environment

The construction work environment presents innumerable challenges and opportunities to construction personnel (Abioye et al., 2021). Within the construction environment, workers perform physically and mentally demanding tasks, causing fatigue (Xing et al., 2020; Namian et al., 2021). The type of work being executed within the construction environment, the team that conduct such tasks, and the construction contracts adopted vary endlessly (Helmrich & Chester, 2022). Thus, rendering the construction work environment uncertain, complex, demanding, and risky (Helmrich & Chester, 2022). Nevertheless, the construction work environment can be rewarding, especially to those who learn how to manage the challenges presented by construction undertakings (Purwanto, 2020; Getu et al., 2021).

The workers in construction work environment are required to perfom tasks that inflict physical and cognitive fatigue risks (Xing et al., 2020; Namian et al., 2021). These fatigue risks are caused by various factors; including environmental conditions such as excessive heat, vibration, noise, poor ventilation, and elevation changes as well as organizational factors such as long work shifts, short breaks, heavy manual labor, awkward postures, and high cognitive demands (Zong et al., 2024). Fatigue risks cause a variety of harmful effects including physical performance declines due to reduced strength, joint aches, and impaired movement; and reduced cognitive functions such as vigilance and hazard recognition; leading to increased accident and injury risk (Zhang et al., 2015; Xing et al., 2020). Zong et al. (2024) linked fatigue to reduced workmanship and lower productivity, noting up to 59% of construction workers who experienced marked tiredness during safety performance evaluations. Therefore, construction work environments should consider subjective fatigue interventions such as work-break cycles, cognitive behavioral strategies, and workload management to reduce the adverse effects of fatigue (Zong et al., 2024).

Current fatigue management legislative and regulatory frameworks in construction include prescriptive rules and fatigue risk management systems for subjective and objective fatigue management (Honn et al., 2019). Prescriptive rules outline the maximum hours that construction personnel should work and minimum rest break times, but may be less effective for non-standard work schedules (Honn et al., 2019). Risk management approaches involve fatigue management procedures like predictive fatigue modeling, workplace monitoring, and post-incident investigation

(Honn et al., 2019). Prescriptive rules including work-break cycles and cool-down arrangements may be necessary to reduce fatigue risks caused by environmental factors such as heat, vibration, and site elevation changes (Heng et al., 2023; Zong et al., 2024). Furthermore, a comprehensive framework for fatigue risk management including optimal staffing, schedule design, monitoring of work hours and sleep, and fatigue symptom monitoring may be integrated to better manage fatigue risks in construction (Phillips et al., 2017). The integration of these measures into safety management systems can enhance fatigue risk mitigation in construction work environments (Phillips et al., 2017).

2.3. Fatigue causes and effects in construction

Fatigue is a decline in a person's ability to sustain normal performance levels and mental alertness (Yung & Wells, 2019). It is a state of feeling tired, sleepy, or exhausted due to insufficient sleep, extended period of anxiety, exposure to harmful environment, as well as prolonged physical and mental work (Sadeghniiat-Haghighi & Yazdi, 2015; Zhang et al., 2015). Fatigue is an antient concept, which has recently got attention within the construction industry since it displays noticeable effects to construction personnel (Grandjean, 1979; Edwards, 1981; Chalder et al., 1993; Horrey et al., 2011; Zhang et al., 2018). Fatigue can be described as a perceived state of 'weariness' as a result of intensive exertion; leading to slower reactions, absentminded slips, memory lapses, lack of attention etc. (HSE, 2024). Physical fatigue can be referred to as a reduction in muscle performance and a speed of movement posed by lifting, bending, or twisting stress (Seo et al., 2016). On the other hand, cognitive or mental fatigue can be understood as a general feeling of exhaustion, which demotivates workers from executing physical and mental tasks (Powell & Copping, 2016).

There are a number of factors that perpetuate fatigue including psychological, physiological, environmental, circadian cycle, and social factors which can reduce cognitive functions and affect the execution of tasks (Powell & Copping, 2016). Physiological fatigue can be divulged easily since it directly affects the muscles through activities such as lifting, handling, and transporting heavy materials from one point to another (Fang et al., 2015; Powell & Copping, 2016). Psychological fatigue usually occur as feelings of tiredness, demotivation at work, etc. Whereas, the environmental, circadian cycle, and social factors influencing fatigue include work environment, work methods, lighting, noise, temperature, the relationship amongst team members, and workers' inability to adapt to the work environment and work activities (Hallowell, 2010; Guimarães et al., 2013).

2.4. Types of fatigue affecting construction personnel

Fatigue can be characterised in two ways, namely, cognitive (mental) and physical fatigue (Grandjean, 1979). The difference between these two types of fatigue is that cognitive fatigue diminishes the cerebral and behavioural performance, whereas physical fatigue decreases the capacity to perform physical activity (Caldwell et al., 2019). Cognitive fatigue is caused by sleep deprivation and sleep desynchronisation, and the combination of these phenomena result in compounded negative effects which can be detrimental to H&S of workers (Readi, 2018). Cognitive fatigue is closely linked with the lifestyle and worker health. Moreover, workers' age should also be considered, since they tend to lose their cognitive capacity over the years, resulting to a mismatch between the work demands and their abilities to perform these tasks (Chang et al., 2009; Hallowell, 2010). Physical fatigue refers to weariness perpetuated by heavy lifting, bending, twisting, repetitive posture, and working in confined spaces (Caldwell et al., 2019).

2.5. Fatigue risks emanating from construction activities

Fatigue is a multifaceted phenomenon that is caused by several factors in the workplace and outside of the workplace. Outside the workplace, sleep apnoea is the most common cause of fatigue (Goodson, 2023). Excess physical and mental work assigned to workers can be regarded as workplace factors perpetrating fatigue (Horrey et al., 2011). The advent of fatigue might be caused by an individual factor, or a combination of interrelated factors such as physical, mental, and environmental stresses (Sadeghniiat-Haghighi & Yazdi, 2015; Bangaru et al., 2022).

Figure 2.1 depicts three sources of construction work fatigue including work environment in which site personnel work, work method of executing tasks, as well as plant and equipment. It further expands on several factors that can perpetuate construction personnel's fatigue risks. These factors encompass physical load, mental load (stress), and environmental load as outlined in Figure 2.1 below.

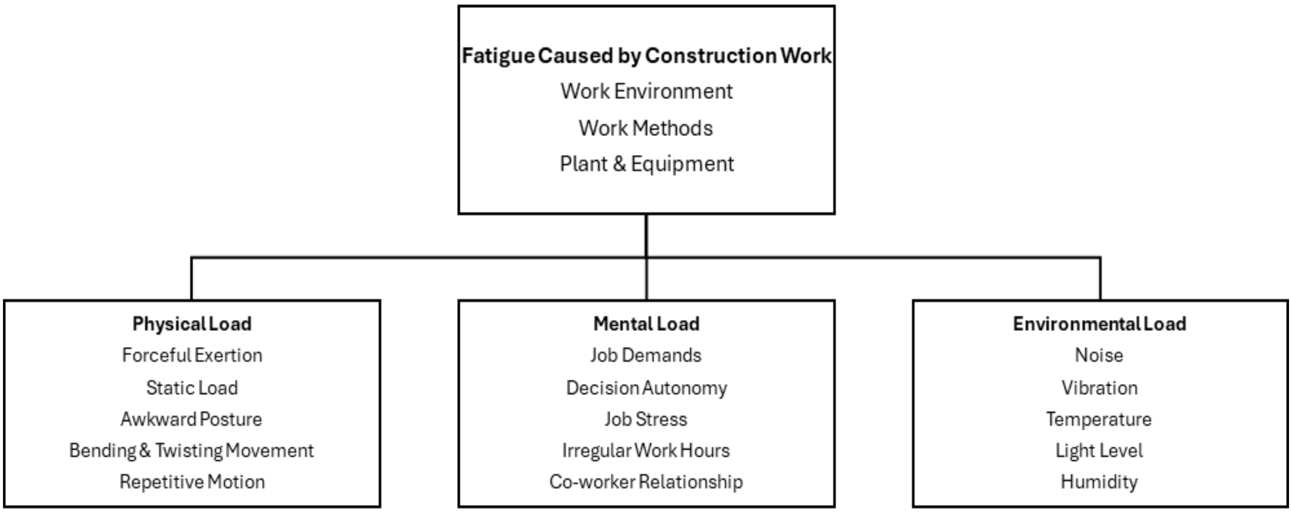

Figure 2.1: Fatigue caused by Construction Work (edited from Bangaru et al., 2022).

To determine fatigue risks emanating from construction work, hazards posed by the work environment should be noted (Korobitsyn & Kuklin, 2016; Wabbels & Bezzola, 2022). Therefore, Table 2.1 shows environmental hazards and risk factors perpetuating fatigue on construction sites including inter alia exposure to ultraviolet rays, drowsiness, and exhaustion.

Table 2.1: Fatigue risk factors caused by the work environment

Environmental Hazards	Fatigue Risks in the Work Environment
Blind Spots	• Fatigue/Concentration
Integration of digital plans to real production plans	• Emotions • Mental States • Physical Condition.
Air temperature, humidity, pressure, noise, light, and proximity within the work environment	• Physical condition (fatigue, overall health, analysis of endurance). • Energy expenditure (calories).
Ultraviolet rays	• Fatigue • Drowsiness • Exhaustion
Poor housekeeping	• Stress • Alertness, leading to exhaustion
Confined Work areas	• Heat stress and Cold stress • Awkward postures

Sources: (Al-Bouwarthan et al., 2019; Caldwell et al., 2019).

2.6. Fatigue risks caused by construction work methods

The construction industry is heterogenous and diverse in nature (Getu et al., 2021). Therefore, the construction work is performed in various segments, namely architectural and industrial. Architectural segment involves the construction of residential, commercial, and institutional buildings (Simons et al., 2017). The industrial segment encompasses facilities such as water treatment, refineries, factories, roads, processing plant, bridges, dams, transmission lines, utilities, airports, and pipelines known as “engineering construction” (Getu et al., 2021). The type of work executed in these segments consist of new construction, renovation, remodelling, reuse, and restoration of existing facilities (Simons et al., 2017). As such, the practical work comprises plumbing, electrical installation, bricklaying, painting, consulting, designing, supervision, plant and equipment operation, cleaning, excavating, etc. (Cartlidge, 2019). These construction undertakings necessitate workers to use different work methods to execute tasks on site which pose innumerable hazards and risks.

Table 2.2 highlights performance hazards that might be present during construction undertakings and further outline the resultant fatigue risks stemming from the work methods. For example, working in complex projects could cause stress and sleep apnoea as shown in Table 2.2.

Table 2.2: Fatigue risk factors emanating from work methods

Performance Hazards	Fatigue Risks Arising from Work Methods
Body temperature	• Physical condition (overall health). • Emotions (arousal)
Eye movements	• Fatigue/Concentration
Body movements, Facial expressions	• Emotions • Mental States • Physical Condition (Fatigue) • Energy expenditures (calories)
Blood oxygen saturation, blood pressure	• Physical condition (analysis of endurance)
Heart-rate variability/blood volume pulse	• Emotions (valence and arousal)
Electrodermal activity	• Emotions (arousal)
Loading and Offloading Materials	• Working in awkward positions • Bending and Twisting muscles and ligaments
Working on complex projects	• Stress/mental fatigue • Sleep Apnoea
Executing physically demanding tasks	• Physical fatigue • Drowsiness while working on height. • Lack of alertness while on site.

Sources: (McMorris et al., 2018; Collins, 2019)

2.7. Fatigue risks precipitated by plant and equipment

To delineate fatigue risk factors caused by construction plant and equipment, a clear identification of environmental and performance hazards is necessary (Korobitsyn & Kuklin, 2016; Wabbels & Bezzola, 2022). As a result, Table 2.3 shows the environmental and performance hazards responsible for various kinds of worker fatigue risks in construction. One of the environmental hazards is vibration which could cause musculoskeletal disorders and physical fatigue to construction plant and equipment operators. Refer to Table 2.3.

Table 2.3: Fatigue risk factors emanating from plant and equipment

Environmental & Performance Hazards	Fatigue Risks caused by plant & equipment
Noise/sound	• Mental fatigue
Vibration	• Musculoskeletal disorders • Physical fatigue
Ultraviolet rays	• Drowsiness • Heat stress
Body Temperature	• Heat and cold stress • Physical overall health
Blind spots	• Fatigue/Concentration
Body Movement	• Physical fatigue • Energy expenditure • Awkward postures • Musculoskeletal disorders

Sources: (Aryal et al., 2017; McMorris et al., 2018; Al-Bouwarthan et al., 2019)

2.8. Wearable technology in construction

2.8.1. Definition of wearable technology

WT is defined as wearable items used to monitor and collect personnel real health data for analysis to ensure the workers' health, safety, and wellbeing (Maltseva, 2020). Liu & Poon (2021) defined WT as sensors that are directly or indirectly inserted on human body which generate motions when the worker performs tasks. Wearable technologies are commonly embedded into personal belongings, such as clothes, eyeglasses, belts, wristwatches, mobile devices, shoes, or, directly on the body. The large data collected by WT is usually stored and analysed using Cloud-Based Computing due to its virtually infinite storage and computing aptitudes (Mizani, 2017).

2.8.2. Application of wearable technology in construction

Research has been done in respect to the use of WT and their effects on construction safety and health (Ahn et al., 2019). Choi et al. (2017) explored the factors influencing the adoption of WT on construction sites. The study examined the workers' intentions for the adoption of WT such as smart vests with an inbuilt GPS for position monitoring and wristband-type activity trackers with physiological sensors for physical fatigue monitoring (Choi et al., 2017). The findings illuminated various elements that seeks to motivate construction employees to use WT for the improvement of workplace health and safety and detection of fatigue related risks (Choi et al., 2017).

Proper understanding of the fundamental aspects that influence the adoption of health and safety technologies in the workplace is vital (AL-Sahar et al., 2021). It guides stakeholders and decision-makers in the creation of appropriate strategies for effective management of the implementation process (Othman et al., 2017). Further, an examination of prior and contemporary research on the deployment of modern technologies in various segments demonstrates several factors on which a successful implementation of these technologies depends on (AL-Sahar et al., 2021). These factors encompass Information systems (IS), information technology (IT), enterprise resource planning (ERP) systems, nanotechnology, green building technologies, 3D printing, Building Information Modelling (BIM), the Internet of Things, as well as wearables, which are still in the early stages of development within health and safety (Nnaji & Awolusi, 2021).

2.8.2.1. Types of sensors applicable for fatigue monitoring

There are numerous sensors used for construction health and safety monitoring. These technologies encompass physiological sensor, environmental sensors, location trackers, and proximity sensors (Ahn et al., 2019). Construction personnel frequently face a variety of health concerns posed by the harsh and dynamic work settings, which can influence health and safety performance and overall working effectiveness (Awolusi et al., 2018). To assess the health of ground workers and construction equipment operators, physiological data such as heart rate, breathing rate, body posture, body speed, and body acceleration can be automatically recorded and analysed using various sensors and systems (Awolusi et al., 2018). Some examples of extensively used physiological sensors to detect fatigue on construction sites include physiological status monitoring system, GPS tracking device, electrocardiogram sensors, electromyography sensors, electroencephalography sensors, skin temperature sensors, blood pressure sensors, tilt sensors, breathing sensors, and movement sensors (Awolusi et al., 2018; Lee & Lee, 2018).

These sensors can gather numerous metrics to indicate a construction worker's stress level and health state, which improves the employees' health and safety performance (Ahn et al., 2019). Wearable technology with gyroscopes has progressively been useful in human motion analysis, such as improvement of balance control and reduced falls (Awolusi et al., 2019; Wang et al., 2017). Additionally, the construction work environment poses health and safety concerns to employees due to the intrinsic necessity for specific supplies, lifting of heavy materials, as well as twisting of muscles and body tissues that may be dangerous to construction personnel. Therefore, wearable technology is required to help protect construction personnel from exposure to H&S risks on sites (Choi et al., 2017).

Workers' highly localised real-time health data on factors such as temperature, stress, fatigue, and potentially harmful material handling can be collected while they are executing their routine tasks (Cannady et al., 2024). The recent study conducted by Nnaji and Awolusi (2021) highlighted significant aspects regarding health and safety technology adoption and decision-making in construction, with technology dependability, efficacy, and durability ranking as the most influential predictors. Choi et al. (2017) explored the factors of construction personnel' WT adoption, and the findings illuminated that perceived utility, social impact, and perceived privacy risk aligned to the workers' anticipation to use smart vests and wristbands. Awolusi et al. (2018) supports the hypothesis. Nonetheless, numerous workplace technologies such as smartwatches, patchs, smart textile electrocardiogram sensor imbedded in safety vest, eco-flex, etc. are now being employed on construction sites to monitor HSW factors including fatigue, awkward work postures, vibrations, forceful exertions, repetitive tasks, mental acuity, emotions, stress, safety compliance, and rest breaks (Patel et al., 2021).

2.8.2.2. Physiological fatigue measurement

The adoption of technological measurement methods for physical fatigue is not new (Edwards, 1981; Chalder et al., 1993; Fang et al., 2015). However, there hasn't been a precise measurement tool that has directly detected physical fatigue (Bangaru et al., 2022). Instead, physical fatigue measurement methods have been attributed to fatigue indicators to divulge physiological cues associated to physical fatigue in the workplace (Bangaru et al., 2022). Physical fatigue has been widely measured using clinical methods such as electromyography (EMG) to assess physical activity due to limited fatigue measurement methods (Awolusi et al., 2017). With time, the assessment of heart rate became the effective method for detecting fatigue in the workplace by comparing the heart rate before, during, and after the execution of specific tasks (Bangaru et al., 2022). Fortunately, the introduction of technological implements powered with multiple sensors such as actigraphy, has made it possible to measure fatigue during construction undertakings on site (Aryal et al., 2017; Awolusi et al., 2017; Powell & Copping, 2016; Zhang et al., 2017).

Zhang et al. (2015) developed the Fatigue Assessment Scale for Construction personnel (FASCW) to evaluate the fatigue of construction personnel. The results indicated that the FASCW can be considered a capable instrument to evaluate fatigue and understand its symptoms in construction personnel (Zhang et al., 2015; Li et al., 2016). Yung & Wells, (2019) argues that the human body demonstrates the measurement of physical fatigue in various ways. However, the application of these methods is restricted since they are developed for specific objectives (Zhang et al., 2015).

According to Zhang et al. (2018), the FASCW fatigue measurement method is consistent with the EMA framework (Park et al., 2023) and can be categorized into subjective and objective assessment techniques as shown in Figure 2.2 below. Thus, deciphering the objective assessment into physiological and kinematic data detecting WT such as heat rate data, EMG activity data, as well as motion smoothness metrics. Figure 2.2 demonstrates a simple process of measuring physical fatigue of workers during project undertaking.

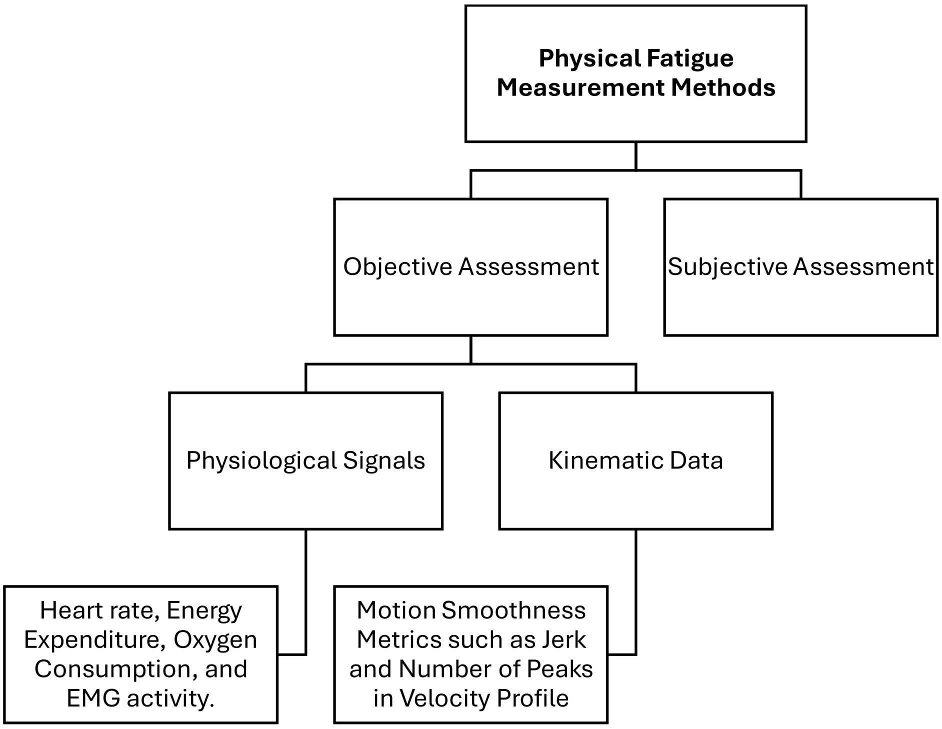

Figure 2.2: Physical Fatigue Measurement Methods (Edited from Bangaru et al., 2022).

2.8.2.3. Cognitive fatigue measurement

Cognitive fatigue can be measured using two technological approaches which are predictive and reactive technological detection mechanisms (McMorris et al., 2018; Zhao et al., 2017). Predictive technology examines a person’s sleep to determine if fatigue will occur and predict when that will happen to decide on the appropriate intervention, and root-cause treatment (Techera et al., 2018; Sanchez et al., 2015; Readi, 2018; Low et al., 2019). Reactive technologies, on the other hand, only detect fatigue once physical symptoms are visible (Papa et al., 2015; Vasconcelos et al., 2016; Zemková et al., 2021). They do not address the root cause of fatigue which might be sleep apnoea, inadequate or poor sleep (Readi, 2018).

Figure 2.3 displays the process of measuring mental fatigue. The mental fatigue measurement mechanisms are divided into two, namely, reactive, and predictive with distinct data. The reactive controls engender EEG monitoring, driver monitoring, psychomotor vigilance task, and telematics analysis. While the predictive controls generate biomathematical modelling which is applied to individual sleep data through actigraphy and polysomnography technology as indicated in Figure 2.3.

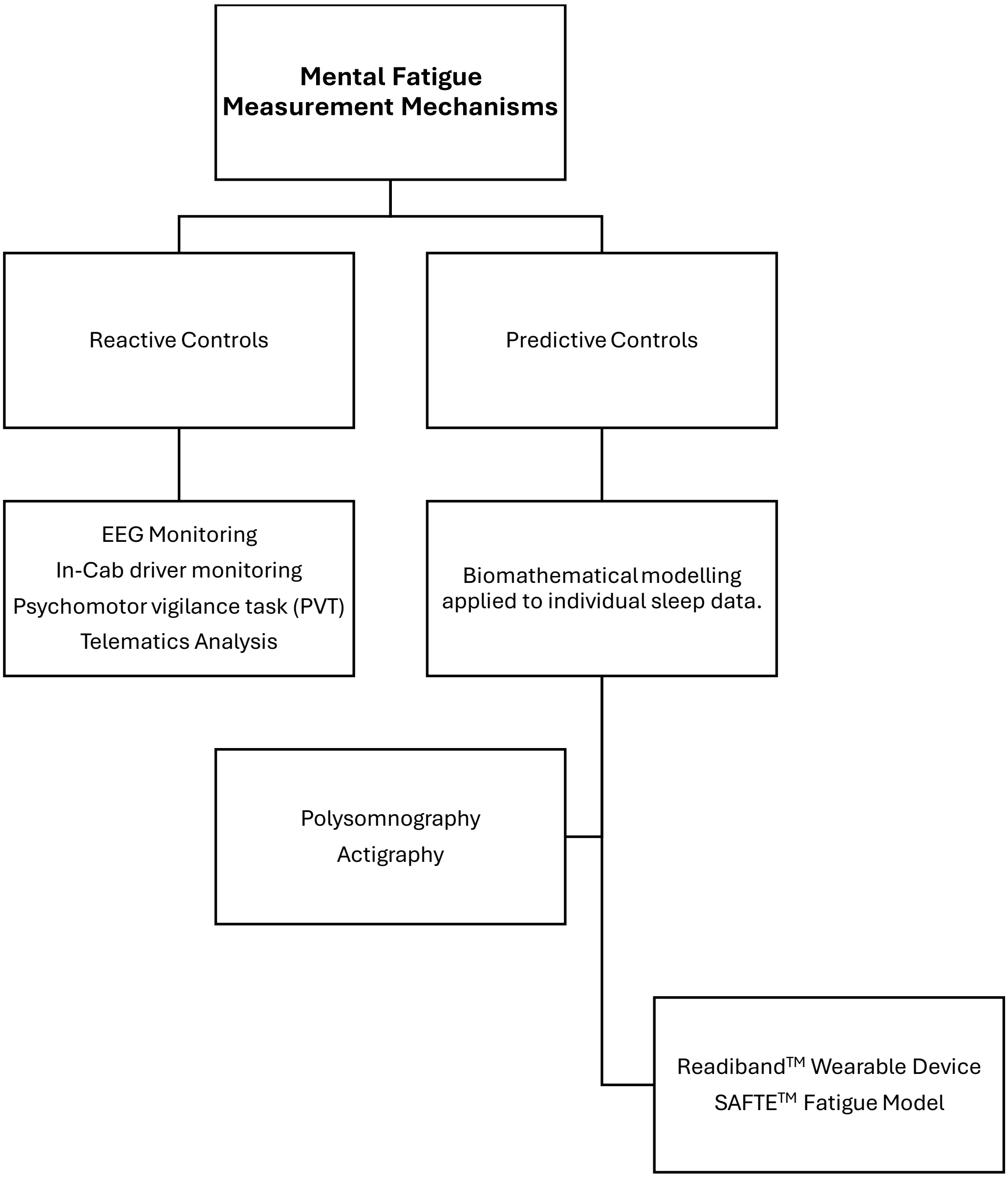

Figure 2.3: Fatigue Technological Measurement Mechanisms (Edited from Kunasegaran et al., 2023).

2.8.2.4. Types of wearable technology used to monitor fatigue risks

Table 2.4 indicates how WT can be used to monitor workers' fatigue during construction undertakings on site. For instance, WT including wristbands powered with pressure sensors can help detect blood pressure which can be used to measure fatigue (Sempionatto et al., 2020).

Table 2.4: Wearable technology best practices in construction

Sensor type	Wearable Technology	Best Practices	Sources
Two photoplethysmography sensors	Sensor	Blood pressure Pulse	(Lokharan et al., 2017) (Lazazzera et al., 2019)
Pulse oximeter	Earphone (Bragi)	Blood oxygen saturation level	(Muzny et al., 2020)
Potential difference	Patch	Blood pressure	(Sempionatto et al., 2020)
Pressure sensor	Wristband (e.g., iHealth, Omron)	Blood pressure	(Sempionatto et al., 2020)
Temperature sensor	Earpiece (e.g., Cosinuss one earpiece)	Body and skin temperature	(Koydemir & Ozcan, 2018)
Temperature sensor	Watch (e.g., Basis)	Body and skin temperature	(Cardona & Solanki, 2021)
Piezoresistive	PEDOT: PSS	Body temperature sensing	(Koydemir & Ozcan, 2018)
Piezoelectric	PZT Fiber	Energy harvesting	(Caliò et al., 2014)
Piezoresistive	Graphene	Finger motion detecting	(Gupta et al., 2022)
Pulse Oximeter	Earring (e.g., Ear-O-Smart)	Heart rate	(Lochner et al., 2014)
Capacitive	Organic TFT	Human pulse wave	(Nagamine et al., 2021)
Capacitive	POMS	Power management	(Kilani et al., 2020)
Capacitive	Eco-flex	Pressure imaging	(Pignanelli et al., 2019)
Accelerometer	Belt accessory (e.g., Spire)	Respiration rate	(Koydemir & Ozcan, 2018) (Ghosh et al., 2021)
Piezo-resistive sensor	Smart textile electrocardiogram sensor	Respiration rate	(Ghosh et al., 2021)

2.8.3. Wearable technology for construction personnel's wellbeing

The construction personnel are exposed to high levels of fatigue, occupational injuries, illnesses, and fatalities, as opposed to other industries (Awolusi et al., 2020). Among the construction personnel that lose their lives on site daily, the majority can be easily assisted by detecting fatigue before it leads to various complications and injuries (Awolusiet al., 2020). Traditional methods of H&S monitoring pose many difficulties when detecting latent worker health factors, hence, the application of WT would help monitor real-time health information of site personnel. Marakhimov &

Joo (2017) suggests that managing the health monitoring of workers while involved in physical work is crucial for the reduction of fatigue-related injuries and fatalities. Therefore, the application of WT is important within the construction industry to monitor various health issues including fatigue, cardiovascular diseases, heart attacks, heat exhaustion, sleeplessness, high blood pressure, heatstroke, etc. (Choi et al., 2017).

Wearable technology has proven to have improved efficiency in the workplace through remote employee monitoring and the usage of helmet camcorders to assist construction personnel during fieldwork (Fernández-Caramés & Fraga-Lamas, 2018; Nath et al., 2017; Awolusi et al., 2018). These technologies have further contributed to finding effective solutions to health problems such as fatigue that arise in the workplace unexpectedly (Awolusi et al., 2018). Numerous construction enterprises are crammed with risky construction activities which are predominantly executed by workers (Packard et al., 2019). As a result, tools such as WT become more active and realistic for construction health and safety risks mitigation (Çiçek, 2015). Studies have highlighted the limitations in detecting the health factors. Nonetheless, WT is effective in sleuthing hidden health effects that transpire because of construction activities or biologically (AL-Sahar et al., 2021).

2.8.4. Adoption of wearable technology in construction work environments

Construction personnel experience various ergonomic hazards when conducting construction activities on site (Kulkarni & Devalkar, 2018). This reality results to countless H&S risks including fatigue, musculoskeletal disorders, injuries, and fatalities (Izci et al., 2023). Fortunately, WT such as a smart safety vest equipped with sensors for activity, posture, heart rate, breathing rate, and core body temperature can proactively detect awkward bending, twisting, reaching, gripping, and repetitive events during heavy lifting (Xue, 2019). Thus, providing real-time safety alerts to correct the construction worker's posture (Patel et al., 2021). The purpose of introducing WT in construction undertakings is to improve organisational performance by elevating workers' competencies and capabilities (Schaefer & Scott, 2016; Manoram & Panghal, 2023). This implies that WT can enhance workers' performance by mitigating limitations imposed by their fatigued bodies and mental state (Okhifun, 2020).

WT has been proven effective in monitoring construction personnel's H&S risks emerging from the work environment and work methods used on site (Caldwell et al., 2019; Readi, 2018). The construction personnel work in a complex, uncertain, and extremely dangerous environment perpetrating countless psychosocial harm, musculoskeletal disorders, ergonomic hazards, etc. (Al-Bouwarthan et al., 2019). Therefore, to avoid damage to ligaments, muscles, joints, and tendons; the selection of suitable WT equipped with physiological sensors, motion sensors, location sensors, and environmental sensors is necessary (Aryal et al., 2017; Zhang et al., 2017; Techera et al., 2018; Sherratt et al., 2023).

WT could help workers monitor fatigue risks by determining various physiological signals such as heart rate variability (HRV), skin temperature, heart rate, electromyography (EMG), galvanic skin response (GSR), and electroencephalogram (EEG) (Maltseva, 2020; Imran et al., 2024). The analysis of these signals would inform fatigue risk factors and fatigue indicative elements including decreased HRV, increased heart rate, varying brainwave activity, etc. (Svertoka et al., 2021; Sherratt et al., 2023; Imran et al., 2024). It could also alert construction personnel about the noise levels, temperature, and blind spots; enhancing their situational awareness when executing tasks on site (Friemert et al., 2023). WT makes construction personnel's situational awareness and HSW possible because of its ability to monitor environmental conditions and H&S hazards on site in real-time (Chandu et al., 2024). Therefore, the adoption of WT for fatigue risks monitoring in construction processes can leverage workers' engagement with work and ensure productivity as well as good health, safety, and well-being (Awolusi et al., 2017). Robson et al. (2016 cited in Sherratt et al., 2023) proposed that risk elimination, productivity extension, competence elevation, and enriched work experience are some of the keyways in which worker engagement can be enhanced during the implementation of tasks on site (Friemert et al., 2023; Sherratt et al., 2023).

WT enhances construction personnel's competences and attune their ability to undertake construction tasks using WT such as smart earphones which can acclimate the environmental noise levels to reduce information distortion (Robson et al., 2016). Moreover, construction personnel can be informed of their stress levels using an activity wristband to detect their pulse (Ajunwa et al., 2021). To make construction work more enjoyable and rewarding, a safer work environment, improved work routines, and enhanced work conditions to elevate employee competence are necessary. Therefore, adopting WT has the potential to allow workers an opportunity to conduct their tasks in a safe and healthy work environment (Patel et al., 2021; Sherratt et al., 2023; Maltseva, 2020).

2.9. Wearable technology to monitor construction workplace fatigue

Various wearable technologies have been identified and tested for fatigue risks detection on construction work environments. Table 2.5 displays the classification, components, and application of WT to monitor workers' fatigue risks on construction sites. For instance, a chest device powered with activity, posture, heart rate, breathing rate, and core body temperature sensors can monitor human movement and provide 24/7 health and safety observations in extreme environments as indicated in Table 2.5.

Table 2.5: Wearable technology used for fatigue detection in construction environment

Classification of Wearable Technology	Components of Wearable Technology	Wearable Technology Application
Vest, Harness, helmets, PPE	Full-body harnesses, lifeline systems, anchorage connectors	Fall protection, machine operations, assembly, demolition, remediation, electrical jobs
Chest Device	Sensors for activity, posture, heart rate, breathing rate, core body temperature	Mobile human monitoring; 24/7 health and safety observations in extreme environments
Helmet	Sensors for noise, gas, temperature, and pressure; integration to external sensors	Real-time situational awareness and location monitor; audio and video features
Chest Harness	Sensors for heart rate, body temperature, breathing rate, posture	Real-time measurement of vitals; knowledge of location and health status; manage safety
Patch	Biosensors for heart rate, sweat, temperature, activity	Real-time reports of heat stress indicators; worksite heat assessment; training and consultation
Belt	Eight sensors, vibration alert response sensor, GPS, ABS belt buckle	Collects data on location, activity, and environment; identify risky activities; haptic response
Headset	motion sensors, GPS, digital microphones, 16 MP camera, 4-axis image stabilization	Hands-free digital workflow, virtual assistance, remote mentoring, data visualization
Safety button	Access to mobile phone features, Bluetooth connectivity, lithium batteries	Send alerts and location data, press unique buttons for non-emergency or emergency response
Clip	Three-axis accelerometer, gyroscope, altimeter	Fall alerts; self-alerts and logging
Chest device	Sensors for heart rate, breathing, activity, posture, accelerometery, impact	Track body vitals, biomechanical metrics, heat stress risks, physical load monitoring

Sources: (Harari et al., 2018; Wilson, 2018; Haghighi et al., 2020; Patel et al., 2021)

2.10. Wearable technology to monitor fatigue stemming from work methods

Several wearable technologies are used to detect fatigue during work in construction to determine the work methods that perpetuate fatigue on site. Table 2.6 demonstrates wearable technologies and their use in construction. For instance, smart gloves powered with pressure sensors in five fingers embedded processor, actuator, and battery to strengthen gripping and grasping action, and adjust applied force and balance between fingers. Refer to Table 2.6.

Table 2.6: Wearable technology used to detect fatigue during construction undertaking

Classification of Wearable Technology	Components of Wearable Technology	Wearable Technology Application
Glove	Pressure sensors in five fingers embedded processor, actuator, battery	Strengthen gripping and grasping action; adjust applied force and balance between fingers
Chest device	Sensors for heart rate, breathing, activity, posture, accelerometery, impact	Track body vitals, biomechanical metrics, heat stress risks, physical load monitoring
Belt device	Inertial measurement units, alert system	Detect high-risk bending, twisting, and reaching
Exoskeleton	Mechanical support system, driven by pulleys, no electrical power	Distribute upper body weight; reduce fatigue and muscle stress
Harness	Motion sensors, ML analytics, posture feedback system	Measure risk of musculoskeletal injuries, give real-time safety score, follows OSHA lifting guidelines
Flexible band	EEG sensors, brainwave technology detectors, Bluetooth communication	Measure fatigue and alertness at real-time; eliminate microsleeps; support wellness
Shoes	Force and motion sensors, control boards	Measure gait changes, impact, and fatigue

Sources: (Andersen et al., 2017; Harari et al., 2018; Haghighi et al., 2020; Patel et al., 2021)

2.11. Wearable technology to monitor fatigue for plant and equipment operators

Construction plant and equipment present various ergonomic and fatigue risks which can be detected using WT. Table 2.7 displays WT classification, components, and application on site when operating plant and equipment. For instance, a smart helmet powered with sensors for noise, gas, temperature, heat stress, and pressure could assist plant operators with real-time situational awareness, location monitoring, as well as audio and video features while conducting construction activities on site (Patel et al., 2021). Refer to Table 2.7 for the application of WT to monitor plant and equipment operators' fatigue on site.

Table 2.7: Wearable technology to detect fatigue for plant and equipment operations

Classification of Wearable Technology	Components of Wearable Technology	Wearable Technology Application
Vest, Harness, helmets, PPE	Full-body harnesses, lifeline systems, anchorage connectors	Fall protection, machine operations, assembly, demolition, remediation, electrical jobs
Wrist monitor	Sensors for hand arm vibration (HAV), whole body vibration, noise, gas, dust	Hand Arm Vibration (HAV) risk assessment; tool testing; exposure monitoring; risk control appraisal
Helmet	Sensors for noise, gas, temperature, heat stress, and pressure; integration to external sensors	Real-time situational awareness and location monitor; audio and video features
Chest Harness	Sensors for heart rate, body temperature, breathing rate, posture	Real-time measurement of vitals; knowledge of location and health status; manage safety
Belt	Eight sensors, vibration alert response sensor, GPS, ABS belt buckle	Collects data on location, activity, and environment; identify risky activities; haptic response
Headset	Motion sensors, GPS, digital microphones, 16 MP camera, 4-axis image stabilization	Hands-free digital workflow, virtual assistance, remote mentoring, data visualization
Safety button	Access to mobile phone features, Bluetooth connectivity, lithium batteries	Send alerts and location data, press unique buttons for non-emergency or emergency response
RFID system	RFID tags, display, external alarm, antenna (865 to 927 MHz, 20 feet range)	Alert the driver about the presence of ground workers; prevent collisions and personal injury
Smart Glasses	Eye Tracker	Monitor the drivers and plant operators' fatigue.

Sources: (Harari et al., 2018; Haghighi et al., 2020; Patel et al., 2021; Wan et al., 2021)

2.12. Gaps in the Literature

According to the literature reviewed in this chapter, fatigue is a silent killer that is responsible for a substantial percentage of construction accidents (Faria et al., 2021; Goodson, 2023). Many experiments have been undertaken using WT to investigate fatigue. These experiments have contributed to the development of various frameworks and models (Seong et al., 2022; Park et al., 2023). However, there is a need to develop a WT protocol to evolve fatigue related interventions and propose practical steps to be followed by construction workers when monitoring fatigue risks on site. The literature also presented limited practical application of WT for fatigue reduction in the construction industry. Most tested studies on fatigue monitoring using WT were in the health sector, whereas the construction research encompassed exploratory and explanatory studies with just a few experimental research. Therefore, there is a gap in the development of WT protocols, frameworks, or models within the construction industry. Hence, this research aims to develop a wearable technology protocol that would help inform about fatigue risk factors on construction sites. Table 2.8 indicates sections from which the gaps in literature were retrieved. It further highlights the objectives to which the literature review chapter themes were linked.

Table 2.8: Gap in the literature

Literature Review	**Linked Objectives**				
	1	**2**	**3**	**4**	**5**
Application of wearable technology in construction	x				
Significance of wearable technology for workers wellbeing		x	x		
Adoption of wearable technology in construction work environments		x	x	x	
Fatigue in the construction industry	x		x	x	
Wearable technology to reduce construction workplace fatigue			x		
Wearable technology to reduce fatigue stemming from work methods			x		
Wearable technology to reduce fatigue for plant and equipment operators				x	

2.13. Chapter Summary

This chapter reviewed relevant literature on WT, fatigue, and H&S interventions to better the life of construction workers improving the work environment, methods of work used, and minimise fatigue effects in plant and equipment. The research reviewed in this chapter supports the use of WT for fatigue monitoring to improve construction work environment, work methods, and plant and equipment operations. However, It flagged various gaps towards the adoption of WT in construction projects. These gaps included:

- The absence of a WT protocol to inform about fatigue risks in construction work environments.
- Limited fatigue tests relative to construction operations on sites.
- Absence of direct fatigue monitoring mechanism that does not rely on indicators such as heart rate, pulse, blood pressure, etc.

- Few studies focusing on construction workers' participation in fatigue monitoring and reduction processes on site. Most research have investigated WT as a mechanism for fatigue monitoring, neglecting practical measures for workers when using WT on site.

The next chapters will propose methods and strategies adopted in this research to develop a WT protocol that would help inform about fatigue risk factors on construction sites.

CHAPTER 3: RESEARCH METHODOLOGY

3.1. Introduction

This chapter presents a detailed methodological choice and the research design process of the study. This study used the philosophical stance and research problem to direct the methodological choice. The chapter explained why exploratory concurrent mixed methods research approach was considered appropriate for the study. Furthermore, this section set the procedures to collect, analyse, and report data. Distinct procedures for qualitative and quantitative data collection and analysis were employed in this study due to different purposes they serve. The chapter also explained the strategies used to enhance the validity and reliability of the findings. Finally, the chapter defined the research time horizon and considerations for ethical issues. Then, the chapter concludes.

3.2. Research Design

Research design outlines the overall structure of the study by providing a framework for the entire research project (Gray, 2014). Pawar (2020) suggests that there are nine possible forms of research design, namely, descriptive design, exploratory design, experimental design, longitudinal design, cross-sectional design, casual design, action research design, cohort research design, and case study design. These forms are centred around three types of research design including descriptive, explanatory, and exploratory research designs. The purpose of descriptive design is to provide a picture of a situation, person, or event and highlight how factors relate to one another (Siedlecki, 2020). However, descriptive design cannot explain why an event has occurred and is suitable for research area that have not been thoroughly explored (Siedlecki, 2020). Therefore, where abundant descriptive information exists, alternative research designs including exploratory or explanatory approach is advisable. Explanatory design focuses on causes and reasons and provides evidence to support or refute an explanation or prediction.

Exploratory research on the other hand is suitable when a lot is unknown about a phenomenon or its problem has not been clearly defined (Saunders et al., 2019). It does not aim to provide the final and conclusive answers to the research questions, but merely explores the research topic in depth. As a result, this study adopted an exploratory research design to shape the direction and structure of this research. The exploratory research designed elucidated the topic of this study and explored the research objectives in varying depths without providing a conclusive answer to the main research question of the study. A mixed methods incorporating both qualitative and quantitative data was adopted. The qualitative data was obtained through an in-depth exploration of research questions using semi-structured interviews. The quantitative data was achieved by investigating predetermined variables through survey questionnaires to deduce whether construction personnel accept or reject known fatigue risk factors and WT's adoption and effectiveness in the construction industry.

3.3. Research Onion Model

Research methodology is a general strategy in which a research project is undertaken. It encompasses a system of philosophical assumptions that allow the researcher to understand the research questions and reinforce the choice of research methods (Shirooyehpour & Fazli, 2022). The methodology is a significant element of a dissertation, as it ensures correlation between chosen tools, techniques, and underlying philosophy (Saunders et al., 2019). This research adopted a research onion by Saunders et al. (2016). The research onion delineates the philosophies, approaches, methods, strategies, and further define time horizons, which altogether aligns with the research design and objectives (Leatemia et al., 2022). The adoption of the research onion model necessitates the analysis of the model's appropriateness to future studies. Figure 3.1 displays a six-layered research onion that was used in this study. Comprehensively, the six main layers of the research onion methodology have been established as 1) research philosophy; 2) research approach 3) research strategy; 4) methodological choice; 5) time horizon; 6) techniques and procedures (Saunders et al., 2019).

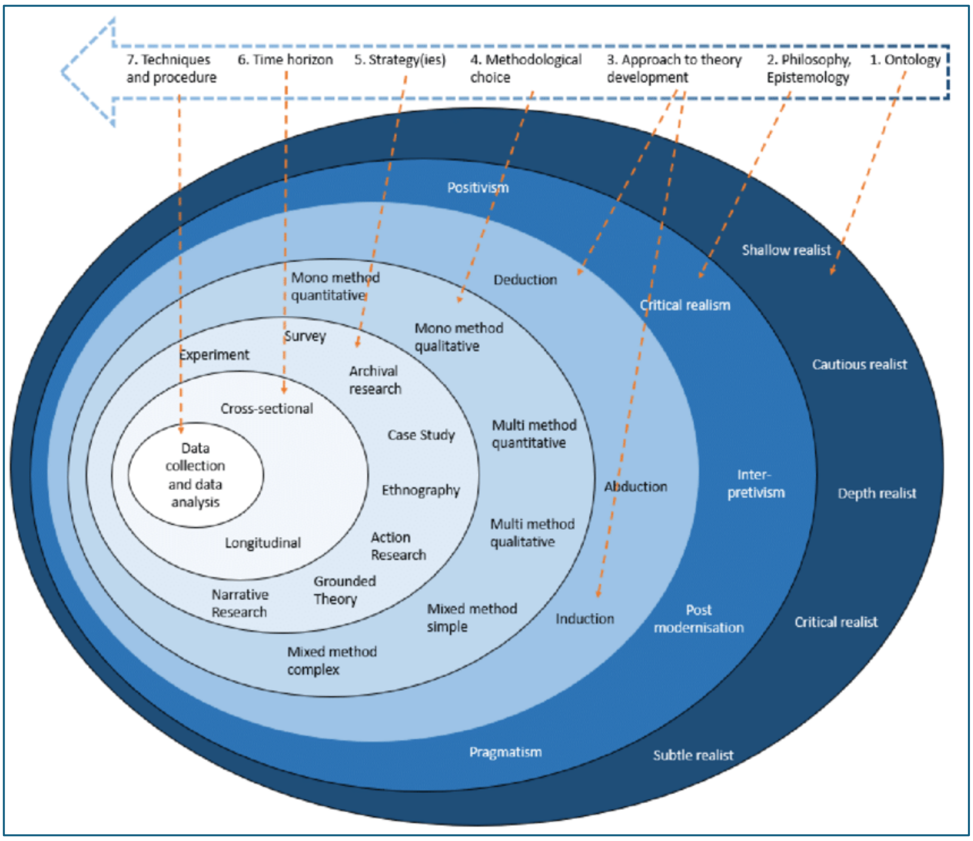

Figure 3.1: Research Onion (Saunders et al., 2019).

3.3.1. Proposed Research Model

Ultimately, all six layers of the research onion were considered for a successful completion of this research project. As such, Table 3.1 highlights the allocation of each of the six research onion layers for the development of a WT protocol for fatigue risk reduction in construction projects. The allotment gives a clear picture for the direction of the research study at hand. Hence, the structural research layers for this study encompass research philosophy, approach to theory development, methodological choice, research strategy, research time horizon, research techniques and procedures as indicated in Table 3.1.

Table 3.1: Structural research layers for the proposed study

The Structural Research Layer	**Choice**
Research philosophy	Pragmatism
Approach to theory development	Abductive
Methodological choice	Mixed Methods
Research strategy	Case Study
Research time horizon	Cross-Sectional
Research techniques and procedures	Semi-structured interviews and survey questionnaires

Source: (Saunders et al., 2019).

3.4. Research Philosophy

The research philosophy answers the question of how knowledge is generated, it expands on the nature of that knowledge, and further explores how it is developed. Saunders et al. (2023) proposed that the understanding of the research philosophy is dependent on the consideration of three types of assumptions which are epistemology, axiology, and ontology. The three worldviews provide a foundation for the philosophies that exist in the first layer of the research onion which include positivism, interpretivism, pragmatism, postmodernism, and critical realism (Saunders et al., 2019).

This study accents the pragmatism philosophy. According to Saunders et al. (2023), pragmatism refers to viewing research through the constructivism and objectivism perspectives or one of the two perceptions. Pragmatism philosophy enabled the researcher to understand the context in which construction personnel work and the types of H&S risks they are exposed to on construction sites. This understanding allowed the researcher to develop a WT protocol that would help reduce fatigue risks on construction sites.

3.5. Research Approach

This study used the abductive research approach incorporating both inductive and deductive research approaches (Saunders et al., 2019). The deductive approach proved relevant in this research because theories and frameworks relative to WT and fatigue have been established (Sheppard, 2020). The absence of a WT protocol to reduce construction personnel fatigue risks brought about the inclusion of the inductive approach to determine how a WT protocol would reduce fatigue to enhance HSW of construction personnel.

3.6. Methodological Choice

This study selected a mixed methods to envisage qualitative and quantitative data. Mixed methods research integrates quantitative research and qualitative research to respond to the central research question (Saunders et al., 2023). As such, this research collected both qualitative and quantitative data to respond to the main research question. The qualitative research data was collected using a case study strategy. Construction personnel were asked to complete survey questionnaires in order to collect quantitative data. As a result, the integrated data (qualitative and quantitative) provide a different kind of information; for instance, the qualitative technique provides open-ended data, whilst the quantitative technique provides closed-ended data. Simultaneously, the quantitative and qualitative data were integrated and analysed separately.

3.7. Research Strategy

For this study, a case study research strategy was employed to collect the qualitative data. A case study is a systematic investigation of an individual, group, community or any other unit in which the researcher examines in-depth data relating to several variables (Heale & Twycross, 2017). This research strategy enabled the researcher to narrow down a broad topic into manageable research questions. Multiple case studies were used to investigate fatigue risk factors and perceived WT effectiveness on construction sites. Case study 1 involved a middle-income residential estate development project in Bloemfontein, Free State province of South Africa. Case study 2 involved the development of a new township in Bloemfontein, Free State province of South Africa. Case study 3 involves a routine road maintenance project located in two South African national roads in the Free state province of South Africa. An overview of the multiple case studies is provided below:

- Case study 1 is situated in Bloemfontein in the Free State province of South Africa. The case study involved a middle-income residential estate development project including bulk excavation, levelling, foundations, paving, parks, water lines, sewer lines, and electricity lines.
- Case study 2 involved the development of a new township in Bloemfontein, Free State province of South Africa. The project covers activities such as bulk excavation, levelling, foundations, construction of the first phase of residential buildings, roads and streets, parks, water lines, sewer lines, and electricity lines.
- Case study 3 involved a routine road maintenance project located in two South African national roads in the Free state province of South Africa. The endeavours encompass various tasks including culverts cleaning, earth channel cleaning, edge build-up removal, grass cutting, guardrail repair and installation, traffic accommodation, median cleaning, repair of fencing, road reserves, cleaning of road shoulders, tree felling, and v-drain cleaning.

The main reason for the adoption of multiple case studies was the distinct nature of construction projects which varied between residential, industrial, and routine road maintenance projects. These projects inflicted different fatigue levels to construction personnel depending on work environments, work methods, and plant and equipment used on site. The findings from these case studies allowed the researcher to develop a WT protocol for fatigue risks reduction on construction sites.

Figure 3.2 demonstrates the research strategy that was followed for the successful completion of this study. This study was categorised into three (3) segments including 'define and design', 'prepare, collect, and discuss', as well as 'analyse and conclude'. The first segment defined the background, problem statement, research questions and objectives. It further explored relevant literature and research gaps. The second segment involved research methods used in this study including the selection of 3 case studies and collection of qualitative and quantitative data from construction personnel working in the construction industry within Free State, South Africa. The third segment analysed the mixed methods research data, developed a WT protocol, and concluded the study by flagging limitations and recommending future practice and research areas.

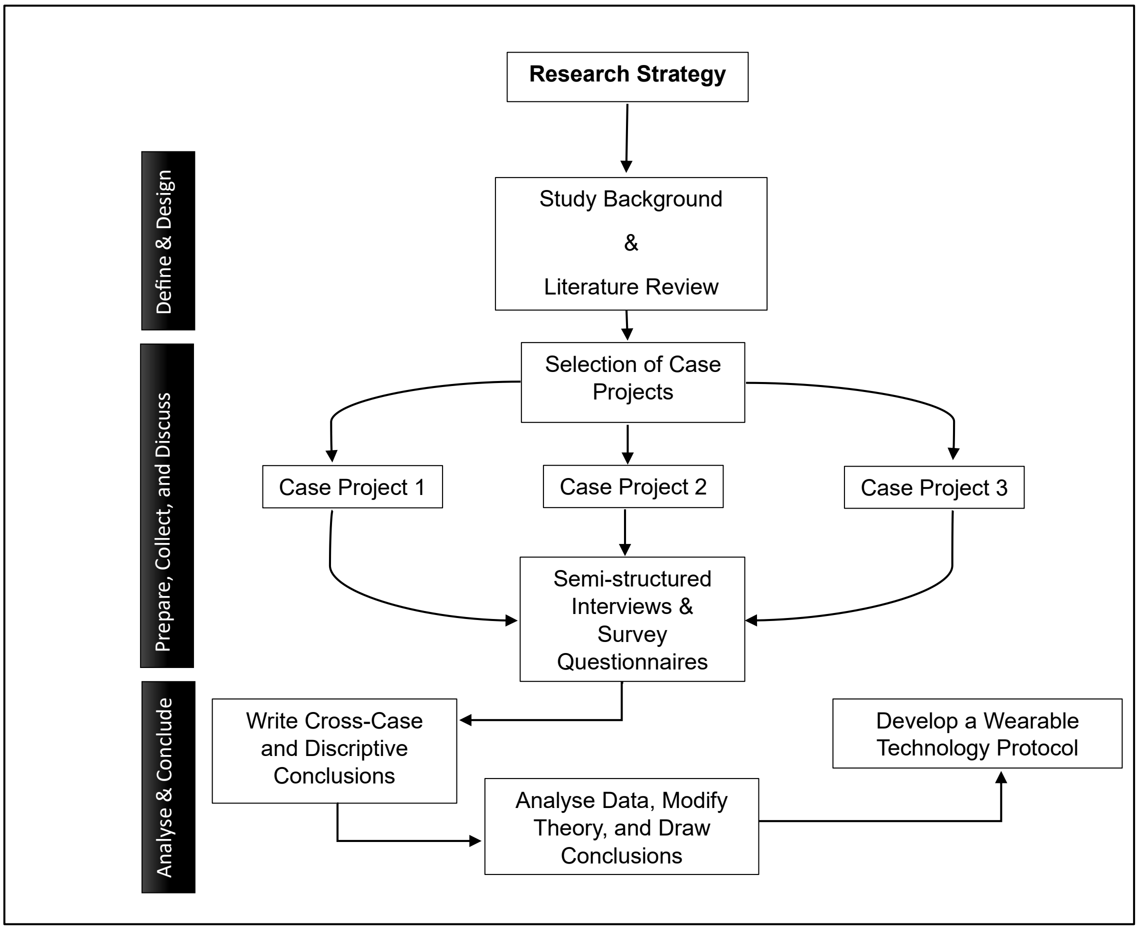

Figure 3.2: Research steps (Modified from Heale & Twycross, 2017; Thomas, 2021)

Additionally, the quantitative data was collected using a survey research technique. As recommended by Creswell and Creswell (2018) a survey is defined as a research strategy intended to offer a quantitative description of attitudes or opinions of a population by examining a sample of the population engaged in the researched subject. A survey questionnaire with closed-ended questions was distributed to construction personnel in the Free State construction industry to collect quantitative data.

The survey questionnaires were developed to answer the study's main research question in accordance with the research objectives listed in Table 3.2. It also drew attention to the parts of the literature review that served as the basis for the survey questionnaire's guidelines, including the tables and figures that shaped the survey questions' research components.

Table 3.2: Research variables for survey questionnaire instruments

Research objectives	**Literature Section**	**Illustrations**
Identify the best practices of using wearable technology to leverage data metrics to investigate fatigue related risk areas	Section 2.5 and 2.8.2.4	Table 2.4, Table 2.1, and Figure 2.1
Describe how to use wearable technology to evolve early fatigue related interventions to help construction personnel.	Section 2.5, 2.8.2.2, 2.8.2.3, 2.9, 2.10, and 2.11	Figure 2.2, Figure 2.3, Figure 2.1, Table 2.5, Table 2.6, and Table 2.7
Evaluate how wearable technology would inform redesigning plant and equipment to reduce fatigue related risk factors.	Section 2.6, and 2.7	Table 2.2, and Table 2.3
Evaluate how wearable technology would inform redesigning plant and equipment to reduce fatigue related risk factors.	Section 2.5, and 2.7	Figure 2.1, and Table 2.3

3.8. Research Time Horizon

This research is a cross-sectional study. The research project commenced in February 2023 and was concluded in November 2024. Concisely, this research project was carried out for the duration of 22 months. The qualitative data collection through semi-structured interviews in 3 case studies spanned five months, from January 2024 to May 2024. The quantitative data collection through survey questionnaires of 116 construction personnel working in Free State construction industry spanned four months, from April 2024 to July 2024.

3.9. Research Techniques and Procedures

The research techniques were divided into two sections which included primary data and secondary data.

3.10. Primary data collection

To ascertain the research objectives of this study, a mixed method was selected, incorporating both qualitative and quantitative data.

3.10.1. Qualitative data collection methods

This study adopted a case study research strategy to collect qualitative data. Three case studies were used to obtain distinct results from residential, industrial, and routine road maintenance projects respectively. The research instruments encompassed semi-structured interviews to allow construction personnel to share their experiences relating to their work environment, work methods, and plant and equipment for plant operators as shown in Figure 3.3. Open-ended semi-structured interviews were conducted on each case project in different intervals. The researcher met with each interviewer in person, mostly on-site in which they work. The interview process was recorded using a cell phone, then transcribed to easily capture and analyse the results.

Figure 3.3 displays a qualitative data collection procedure that was adopted with instrument design for data collection from construction sites.

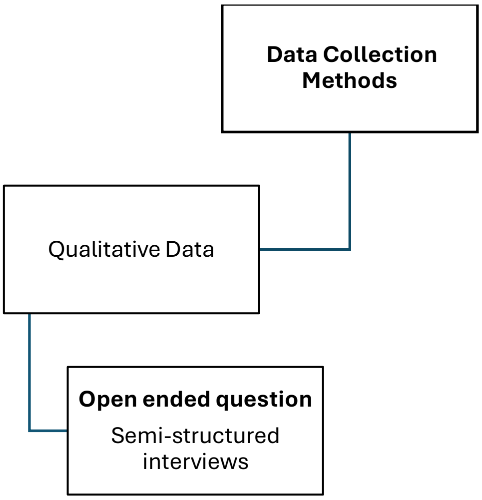

Figure 3.3: Qualitative data collection procedure (**Source:** Researcher)

3.10.2. Quantitative data collection methods

This study also collected quantitative data by administering survey questionnaires to determine construction personnel's experiences of fatigue risks in construction and their perception of WT. Figure 3.4 displays the quantitative data collection procedure to investigate workers' fatigue in the workplace and methods used during construction undertakings. The survey questionnaires made use of closed-ended questions to better understand the research phenomena as shown in Figure 3.4. The survey questionnaires used a One (1) to five (5) Likert Scale. The research instruments were printed, and hardcopies administered to construction personnel in person. The statistical instruments were distributed to professional, managers, plant operators, artisans, forepersons, and general workers. The researcher administered 120 hardcopies of survey questionnaires to construction personnel and only 116 surveys were returned.

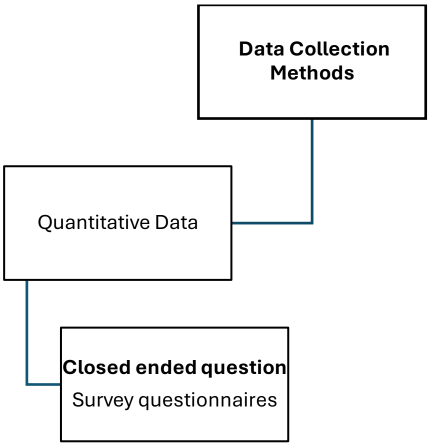

Figure 3.4: Quantitative data collection procedure (**Source:** Researcher)

3.11. Secondary data collection

This research harnessed secondary data through a narrative literature review from various databases. The researcher reviewed databases such as Scopus, Science Direct, EBSCOHost, Emerald, etc. to gather information in response to the main research question and problem statement of the study. Upon selecting research databases, the researcher examined abstracts, methodologies, and recommendations of different articles sourced for relevance and reliability. Thereafter, relevant articles were thoroughly scrutinised to gather information about WT, fatigue, work environment, work methods, plant and equipment, and protocols. Thus, responding to the central research question, aim, and objectives.

3.12. Research Population and Sample

3.12.1. Qualitative data sampling procedures

This research adopted a multiple case study design to attain qualitative data. The researcher used 3 case projects including an estate development project, township development project, and routine road maintenance project. Open-ended semi-structured interviews were conducted for each case project and the RPs were interviewed relative to their affiliation under any of the 3 case projects. A non-probability sampling using a heterogenous purposive sampling technique was adopted to select interviewees. The researcher selected 3 case studies purposefully to conduct interviews. The interviewees composed 48 construction personnel across 3 case projects (Case 1 = 27, Case 2 = 9, and Case 3 = 12) to obtain diverse workers' expertise and experiences. The researcher only interviewed construction personnel involved in any of the 3 case projects considering their distinct occupation and involvement in the project. For instance, all 3 case projects involved management, artisans, plant operators and general labour to understand their varying perspectives and experience of WT and fatigue risks.

The research population was made up of all construction personnel within the construction industry and the sample of this study composed 48 construction personnel across 3 case projects in Free State, South Africa. For example, the interviewees included tilers, TLB operators, tipper truck operator, bobcat operator, site supervisors or forepersons, health and safety officer, carpenter, painter, welder, roof carpenter, general workers, estate manager, quantity surveyors, cleaner, storeroom helper, plumbers, bricklayers, construction manager, broomer operator, smooth drum roller operators, diesel truck operator, steel fixing specialist, shuttering specialist, grader operator, driver, brush cutter operators, and director or supervisor from all three case projects.

Case study 1 involved an estate development project. The research sample for this case study composed members of the construction team including general workers, artisans, plant operators, and managers. A total of twenty-seven (27) interviews were conducted as shown in Table 3.3.

Case study 2 involved the development of a new township in Bloemfontein, Free State province of South Africa. The research sample for this case study composed members of the engineering team including artisans, plant operators, and managers. A total of nine (9) interviews were conducted as indicated in Table 3.3.

Case study 3 involved a routine road maintenance project located in two South African national roads in Free state province of South Africa. The research sample for this case study composed members of the engineering team, contractor, and subcontractors including plant operator, general workers, and managers. A total of twelve (12) project participants were interviewed as indicated in Table 3.3.

Table 3.3: Demographic of research participants

Case Study	Variables		N	(%)
Case Project 1 *(Estate Development)*	Designation	Artisans	11	41.0
		Plant Operators	4	15.0
		General Workers	3	11.0
		Managers	9	33.0
	Total		**27**	**100.0**
	Experience	0 – 5 years	13	48.0
		6 – 10 years.	8	30.0
		11 – 15 years.	3	11.0
		16+ years.	3	11.0
	Total		**27**	**100.0**
	Qualification	Below Matric & Matric	15	56.0
		College Certificate	4	15.0
		Undergraduate	6	22.0
		Postgraduate	2	7.0
	Total		**27**	**100.0**
Case Project 2 *(Township Development)*	Designation	Artisans	2	22.0
		Plant Operators	5	56.0
		Managers	2	22.0
	Total		**9**	**100.0**
	Experience	0 – 5 years	2	22.0
		6 – 10 years.	4	44.0
		11 – 15 years.	1	11.0
		16+ years.	2	22.0
	Total		**9**	**100.0**
	Qualification	Below Matric & Matric	6	67.0
		College Certificate	1	11.0
		Undergraduate	2	22.0
	Total		**9**	**100.0**
Case Project 3 *(Routine Road Maintenance)*	Designation	Plant Operator	5	42.0
		Managers	4	33.0
		General Worker	3	25.0
	Total		**12**	**100.0**
	Experience	0 – 5 years	10	84.0
		6 – 10 years.	0	0.0
		11 – 15 years.	2	16.0
	Total		**12**	**100.0**
	Qualification	Below Matric & Matric	11	92.0
		Undergraduates	1	8.0
	Total		**12**	**100.0**

(**Source:** Researcher)

3.12.2. Quantitative data sampling procedures

The research population encompassed all construction personnel within the construction industry and the sample of this study composed 116 construction personnel working in construction projects.

For example, the RPs included, managers, contractor, subcontractors, site agents, foremen, artisans, and general workers as indicated in Table 3.5. A probability sampling through simple random sampling technique was adopted to select RPs for the statistical data (McCombes, 2019). This was achieved through a random selection of construction personnel working in Free State construction industry to administer survey questionnaires for data collection. The survey questionnaires were printed, and 120 copies given to construction personnel working in Free State construction industry. The researcher drove around Bloemfontein, Free state construction sites and consultants' offices to distribute survey questionnaires to construction personnel. At the end of the 4-months period, only 116 survey questionnaires were populated by construction personnel which were then used in this study.

Table 3.4 displays the RPs' demographic profile including their age, gender, experience, and qualification.

Table 3.4: Research participants' demographic profile

Variables		**N**	**(%)**
Age	20 – 29 years	33	28.0
	30 – 39 years	46	40.0
	40 – 49 years	30	26.0
	50+ years	7	6.0
Total		**116**	**100.0**
Gender	Male	92	79.0
	Female	24	21.0
Total		**116**	**100.0**
Years in the current position	0 – 5 years	57	49.0
	6 – 10 years.	34	29.0
	11 – 15 years.	14	12.0
	16+ years.	11	10.0
Total		**116**	**100.0**
Qualification	Below Matric & Matric	37	32.0
	Nated College Certificate	12	10.0
	Undergraduate	56	48.0
	Postgraduate	11	10.0
Total		**116**	**100.0**

(**Source:** Researcher)

Table 3.5 below shows the RPs' designation and professional advancement within the construction industry.

Table 3.5: Research participants' designation and professional registration

Variables		N	%
Designation	Professionals/Consultants	23	20.0
	Artisans	37	32.0
	Plant Operators	6	5.0
	General Workers	2	2.0
	Managers	48	41.0
Total		**116**	**100.0**
Professional Registration	ECSA	8	7.0
	SACPCMP	8	7.0
	SACAPSA	5	4.0
	SACQSP	3	3.0
	N/A	92	79.0
Total		**116**	**100.0**

(**Source:** Researcher)

Table 3.6 demonstrates RPs' project involvement including the types of projects they are involved in and the level in which the conduct work on site.

Table 3.6: Research participants' project involvement

	Variable	N	%
Project Type	Residential Building	65	56.0
	Commercial Building	3	3.0
	Industrial/Civil Works	35	30.0
	Institutional Building	13	11.0
Total		**116**	**100.0**
Site Orientation	Ground Level	54	47.0
	Elevated Heights	0	0.0
	Both	62	53.0
Total		**116**	**100.0**

(**Source:** Researcher)

3.13. Instruments Administration

The research instruments were administered in a manner that displayed the researcher's professionalism, which in turn, encouraged the participants to freely engage in the research process. Refer to Annexture A for detailed qualitative data instruments (interview guide) and Annexture B for detailed quantitative data instruments (survey questionnaire guide).

3.13.1. Qualitative data instruments

The qualitative data was collected using open-ended interviews, particularly, semi-structured interviews. The instruments composed two sections, namely general information and interview guide. The first section involved RPs' demographic information, work experience, professional advancements, etc. The second section involved open-ended interview questions to incapsulate the construction personnel' site experiences relative to work environment, work methods, and plant and equipment. The qualitative research questions used in the interview guide were extracted from reviewed literature in chapter 2.

3.13.2. Quantitative data instruments

The quantitative data was collected using survey questionnaire. The instruments composed two sections, namely general information and survey questionnaire guide. The first section involved RPs' demographic information, work experience, professional advancements, etc. The second section involved closed-ended survey questions to statistically analyse construction personnel's fatigue experiences and perceived effectiveness of WT.

3.14. Research Data Analysis

This research adopted a mixed methods to collect and analyse both qualitative and quantitative data (Bhandari, 2022; Bhat, 2023).

3.14.1. Qualitative data analysis

The qualitative data were collected from multiple case studies including an estate development project, township development project, and routine road maintenance project. The researcher conducted open-ended semi-structured interviews and recorded the interview process using a cell phone. A cross-case analysis method was used to analyse the qualitative data from interviews which was then followed by a thematic analysis method to structure the results into themes. The cross-case analysis method was achieved by comparing 3 case studies and deriving similarities to narrow the findings to construction personnel's experiences across all 3 case projects. The researcher also used research objectives to create themes for a clear analysis of the interview results.

3.14.2. Quantitative data analysis

The quantitative data were collected from 116 construction personnel including professionals, managers, artisans, forepersons, plant operators, and general workers involved in construction endeavours. The researcher administered hardcopies of closed-ended survey questionnaires to construction personnel. The descriptive analysis method using Statistical Product and Service Solutions (SPSS) software was adopted to determine the mean scores (MSs) and standard deviation (Std.) for each quantitative data variable.

3.15. Reliability and Validity

This research adopted a mixed methods to collect and analyse both qualitative and quantitative data. Therefore, the reliability and validity of this study was explored for both research methods.

3.15.1. Reliability and Validity of Qualitative data

This research obtained qualitative data from multiple case studies. The results of this study were based on a cross-comparison of research data collected from three case projects. The reliability of this study therefore lies on the interview findings from construction personnel working in different project endeavours. Their practical involvement on site provides a clear perspective of construction personnel's experiences of the work environment, work methods, and plant and equipment operation in construction. A diverse group of construction personnel was interviewed to gather distinct insights relating to fatigue, WT, and HSW.

3.15.2. Reliability and Validity of Quantitative data

This research collected quantitative data from survey questionnaires of 116 construction personnel. The reliability of data obtained from survey questionnaire instrument was established using Cronbach's Alpha measurement to demonstrate the data internal consistency. Table 3.7 below presents the Cronbach's rule of thumb that was used to interpret the internal consistency of the quantitative data in this study. The Cronbach's Alpha was used to assess how well a set of variables and constructs measured the same underlying factors. The variables and constructs were considered reliable when the Cronbach's Alpha score is greater than 0.6, acceptable when it is greater or equal to 0.7, good when it is greater or equal to 0.8, and excellent when it is greater or equal to 0.9. The data was analysed using IBM SPSS Statistics version 29.0.1.1 (Kumar, 2024). Moreover, the survey respondents composed construction personnel registered with professional councils including SACPCMP, SACQSP,SACAP, ECSA, etc, construction managers, quantity surveyors, site agents, artisans, forepersons, plant operators, and general workers. The validity of survey questionnaire instrument was measured by assessing the alignment of research variables with research objectives.

Table 3.7: Cronbach's rule of thumb

Cronbachs Alpha	**Interpretation**
Greater or equal to **0.9**	Excellent
Greater or equal to 0.8	Good
Greater or equal to 0.7	Acceptable
Greater or equal to 0.6	Questionable
Greater or equal to 0.5	Poor
Less than 0.5	Unacceptible

(**Source:** George & Mallery, 2021)

3.16. Research Process

Figure 3.5 demonstrates a research process that was followed to complete this study. The study established the research background, defined the research problem, and determined the research aims and objectives. A thorough review of literature was conducted to explore concepts relating to WT and fatigue. Research methods and approaches were then determined, which propelled the development of the research instruments for the mixed methods study incorporating both qualitative and quantitative data. To obtain qualitative data an interview guide was developed which was analysed using a cross-case and thematic analysis methods. A survey questionnaire guide was developed to collect quantitative data which was then analysed using descriptive analysis method. The qualitative data was compared with the quantitative data to derive correlation and draw conclusions as shown in Figure 3.5.

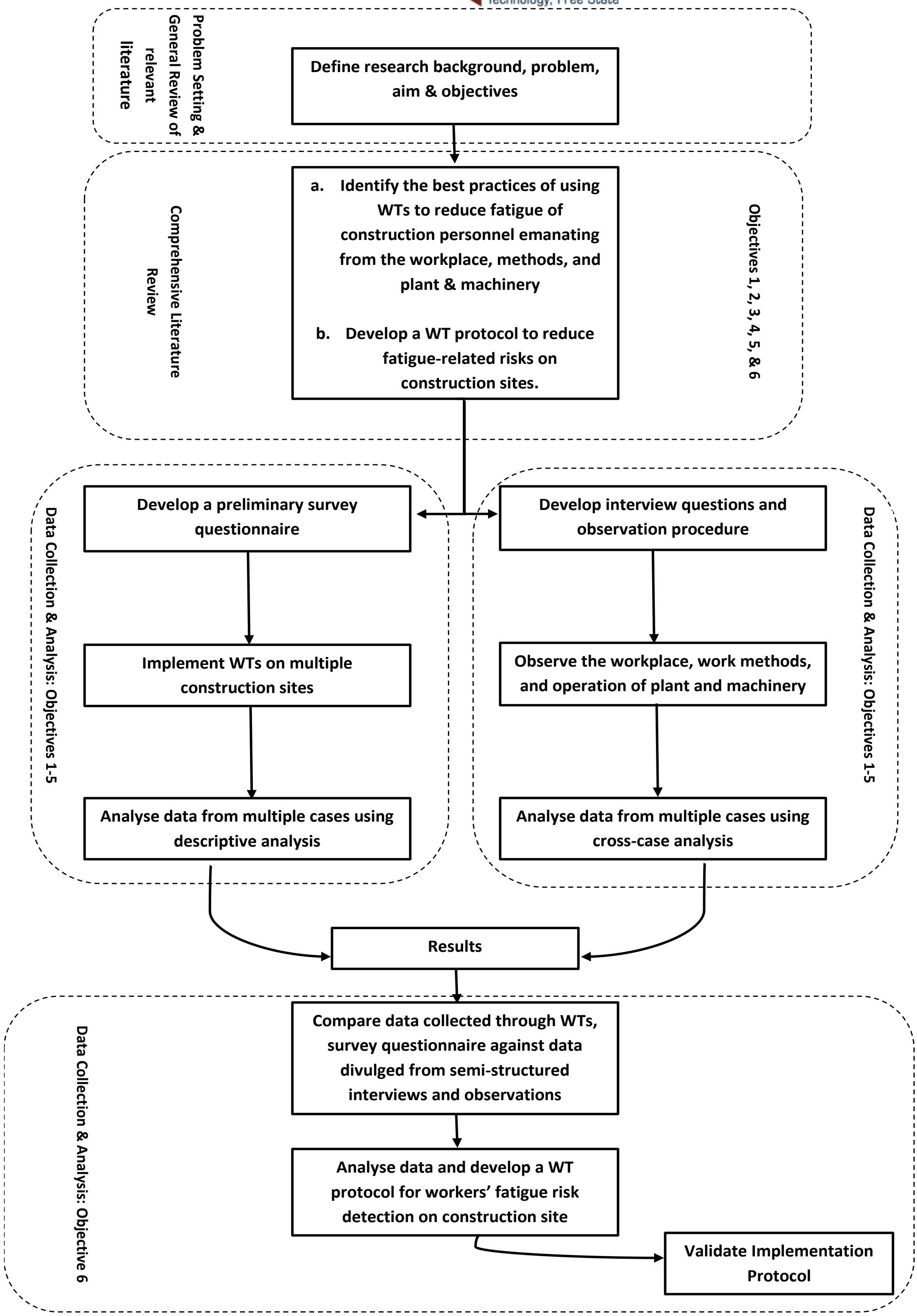

Figure 3.5: The Research Process (**Source:** Researcher)

3.17. Ethical Considerations

The researcher collected data from people and about people in construction. Therefore, ethical issues were considered to ensure transparency, confidentiality of construction personnel sensitive information, and honesty (Mirza et al., 2023). The application for ethical clearance to conduct research in the Faculty of Engineering, Built Environment and Information Technology was done and approved by the FEBIT Ethical Committee (FRIC). The ethical clearance number for this research is FRIC:31/08/2023(2) as shown in Annexture C. Furthermore, the study anticipated ethical issues arising early in this research project and throughout the progression of the research project (Mirza et al., 2023). As such, this study considered the following ethical elements passim the progression of this research project:

Worthiness of the project – The study allowed construction personnel and academia to expand on construction personnel' health to improve health and safety on site. Construction personnel learned that WT is not only a luxury item, but a necessity on site, because it allows the construction phase to proceed smoothly as construction personnel' fatigue levels are monitored throughout the execution phase of the project lifecycle.

Competence boundaries – The researcher obtained a bachelor's degree in construction management, Postgraduate diploma in Health and Safety, and is registered with SACPCMP as Candidate Construction Project Manager. Hence, the researcher has the necessary knowledge to carry out the research that is needed for the study.

Informed consent – The researcher presented the details of the research to the construction personnel that were either being interviewed or completing survey questionnaires to guarantee transparency and honesty with RPs. The researcher also allowed the interviewees and survey participants to consent to the interview or completing a survey questionnaire.

Benefits, costs, and reciprocity – All stakeholders involved in this study gained knowledge on what WT entails and how its adoption in the construction industry would benefit not only construction personnel on site but construction companies in the long run. This study further developed a WT protocol to assist construction personnel to reduce fatigue risk factors on site.

Harm and risk – There were no risks nor harm caused since the researcher handled RPs' information with care and confidentiality.

Honesty and trust – Firm professional relationships were established.

Privacy, confidentiality, and anonymity – Data collected did not require RPs' personal information. The data collected through interviews and survey questionnaires was treated as a value and converted into statistics and analytical graphs for discussion.

Intervention and advocacy – There were no harmful, illegal, or wrongful behaviour during the research process of this study. Therefore, legal advice or enforcement was not required in this research project.

Research integrity and quality – The research was conducted consistent with reasonable standards to ensure successful research outcomes. Moreover, appropriate sampling and data analysis tools were used to ensure research integrity and quality.

Ownership of the data and conclusions – The researcher has full rights to the data collected in this research.

Use and misuse of results – The researcher holds full responsibility of ensuring that the findings are used appropriately according to the research expectations and objectives.

3.18. Chapter Summary

The chapter delineated a detailed framework for the methodological decisions of the research. The philosophical stance, research design, mixed methods using multiple case studies and survey questionnaires have set the tone for a clear research process. This section points to the research approach to address each of the research questions from the problem statement. The research followed an exploratory concurrent mixed research approach to meet the research objectives. The quantitative data was then analysed through descriptive analysis method and the qualitative data was analysed using a cross-case and thematic analysis methods to draw conclusions and recommendations. The strong sample of construction personnel across 3 construction firms adds to the reliability of qualitative data. Moreover, the reliability of statistical data was tested using Cronbach's Alpha coefficient. Ethical practice was considered for data collection, storage, and analysis. Then, the chapter concluded.

CHAPTER 4: RESULTS AND INTERPRETATION

4.1. Introduction

This chapter presents and interprets a mixed methods data incorporating qualitative and quantitative research data obtained from semi-structured interviews and survey questionnaires respectively. The qualitative data were concurrently collected from three (3) case projects in Free State province of South Africa using open-ended semi-structured interviews. The quantitative data were obtained from 116 construction personnel, artisans, managers, plant operators and professionals in Free State, South Africa using closed-ended survey questionnaires. This chapter is subdivided into two sections. The first subdivision presents the interview data from three case projects using themes extracted from each research objective. The second subdivision presents the research demographic data, response rate, and data analysis from survey questionnaires. The chapter aims to understand the nature of fatigue risks that construction personnel within the Free State province are exposed to, their awareness of wearable technology, and perceived need for wearable technology including how they anticipate its effectiveness in monitoring construction work environments, methods, as well as plant and equipment operations. Then, the chapter concluded.

4.2. Qualitative Case Project 1: Estate Development Project

Case project 1 is a middle-income housing development project located in Bloemfontein in the Free State province, South Africa. This estate development project includes construction trades such as bulk excavation, levelling, foundations, paving, parks, water lines, sewer lines, and electricity lines. The case study was used in this research to collect semi-structured interviews. The research sample for this case study involved members of the construction team including general workers, artisans, plant operators, forepersons, supervisors, quantity surveyors, and construction managers. A total of 27 interviews were conducted as shown in the case sample presented in chapter 3, refer to Table 3.3.

4.2.1. Best practices for using wearable technology to investigate fatigue

This sought to address the first research objective which sought to identify the best practices of using wearable technology to leverage data metrics to investigate fatigue related risk areas. The findings were categorised into two themes including ‘fatigue risks experienced by construction personnel on site’ and construction personnel’s perception of wearable technology best practices to investigate fatigue’. The RPs composed 27 construction personnel to better understand their fatigue experiences on site and perception of WT thereof. The information relating to categories of the sample and their work experience is reported in Table 3.3. The majority of construction personnel in this case project had prior experience of using wearable technology such as smartwatches for fitness purposes or casual use, although some of them did not have such experience or knowledge. Therefore, the researcher conducted a presentation on wearable technologies, their uses, advantages and disadvantages, their impact in the medical field and construction projects particularly in the global north, as well as their negative effects on privacy. The purpose of the presentation was to help construction personnel understand wearable technologies and their effectiveness in monitoring various latent factors that could perpetuate health and safety risks on site. As a result, the researcher capitalised on construction personnel's understand of the uses, negative effects, and impact of WT to investigate their perception of WT's effectiveness to monitor fatigue. The main themes that emerged across all RPs in this case project were as follows:

- The construction personnel experienced various mental and physical fatigue risks in this case project.
- The construction personnel believed that WT would help monitor their fatigue risks.
- The construction personnel's experience of using smartwatches gave them confidence that factors such as heart rate, blood pressure, temperature, and activity rate monitoring are best practices of WT and would help monitor fatigue risks on site.

4.2.1.1. Fatigue risks experienced by construction personnel on site

When the RPs were asked about fatigue risks that were experienced by construction personnel on site; all construction personnel in case project 1 mentioned that they experienced various kinds of fatigue risks which affected their levels of productivity, morale, and mental health. The fatigue risks included:

- Conducting construction activities in an environment that is mentally stressful and physically exhaustive.
- Working in an environment that is exposed to ultraviolet rays, causing heat stress.
- Having to worry about work even at home, leading to reduced sleeping period.
- Conducting tasks in a confined work area, forcing workers to work in awkward postures.
- The material storeroom was located far from the work areas, requiring construction personnel to walk long distances exposed to ultraviolet rays to get materials.
- Most of the tasks required construction personnel to exert force, causing exhaustion and sometimes injurying ligaments on a daily bases.
- The construction personnel were sometimes required to work elongated hours conducting repetitive tasks on site, resulting in energy deficience and reduced arletness.

4.2.1.2. Perceived impact of wearable technology to monitor fatigue risks

To determine the perceived impact of using wearable technology to investigate fatigue risks; construction personnel's perceived best practices of WT on site were examined. The health and safety officer, roof carpenter, bobcat operator, and quantity surveyor in case project 1, described the best practices of using WT as its ability to monitor the heart rate using smartwatches. The estate manager, bricklayer, cleaner, 2 forepersons, and welder in case project 1 alluded saying that some of the best practices of WT known to them include pulse, footsteps, and temperature monitoring on site. The carpenter, general worker, storeroom helper, and 3 plumbers in case project 1 stated that other best practices of using WT are its ability to detect internal sickness and inform supervisors and workers timeously. While the painter, tipper truck operator, tiler, 2 supervisors, and 2 bricklayers added that blood pressure monitoring, and fatigue monitoring are the best *practices* of WT. The supervisor in case project 1 said that WT's best practices are its ability to help project teams improve time management, communication of fatigue risks to management and workers, and H&S during project undertakings.

> *"The best practice of WT is that it can notify workers to rest, thus, enhancing productivity since workers will always be on their best energy to work after taking rest breaks",* said the TLB operator in case project 1.

4.2.2. Wearable technology to evolve early fatigue interventions

This section responded to the second research objective which aimed to describe how the use of wearable technology would help inform about fatigue risk factors to help construction personnel. The findings in this section were categorised into two themes, namely, 'WT for early fatigue interventions' and 'improved communication about workers' fatigue risks'. These thematic areas responded to the extent to which WT could help track construction personnel's early fatigue and communicate workers' fatigue to the workers concerned and employers timeously. The RPs composed 27 construction personnel to understand the effectiveness of WT in sleuthing early fatigue risks affecting workers on site. The information relating to categories of the sample and their work experience is reported in Table 3.3.

4.2.2.1. Wearable technology for early fatigue interventions

When the RPs were asked about their peception of wearable technology's effectiveness to inform early fatigue interventions; the supervisors, estate manager, quantity surveyor, forepersons, and storeroom helper in case project 1 said WT could be worn by workers to inform them if it is safe to continue with work or rest if fatigued. The plumber, tiler, 2 TLB operators, Bobcat operator, tipper truck operator, and 3 bricklayers in case project 1 expanded by stating that WT could be used on site to monitor how much energy a worker uses to prevent overexertion. Furthermore, the roof carpenter, painter, carpenter, welder, cleaner, and general worker in case project 1 mentioned that WT could be used to alert workers to hydrate when needed on site.

> *"To evolve early fatigue interventions, WT could be incorporated into personal protective equipment to monitor construction personnel' blood pressure, heart rate, and sugar levels", said the health and safety officer in case project 1.*

4.2.2.2. mproved communication about workers' fatigue risks

The forepersons, painter, welder, 3 bricklayers, 3 plumbers and carpenter in case project 1 stated that, *"WT would allow employers to communicate workers' fatigue levels with construction personnel to ensure sufficient rest times and improved health, safety, and production"*. The 2 TLB operators, tipper tuck operator, bobcat operator, and roof carpenter in case project 1 supported the notion by stating that WT would help notify workers to rest or continue working. In agreement, the quantity surveyor, estate manager, 2 supervisors, and storeroom helper in case project 1 affirmed that WT would certainly help employers to monitor fatigue risks before an injury or fatality occurs on site to warn construction personnel timeously.

4.2.3. Effectiveness of wearable technology for the work environment and methods

This section responded to the third research objective which intended to evaluate how wearable technology would inform about fatigue risks and possible interventions for the work environment and methods of work used by construction personnel. The results in this section were categorised into two themes, namely, 'WT for the work environment and methods of work' and 'improvement of workers' health using WT'. These thematic areas responded to the extent to which workers behaviour, safety compliance, and work demands or activities could be improved using WT to promote workers' HSW in the work environment. The RPs composed 27 construction personnel to understand how they envisage WT helping to inform about fatigue risks and interventions for the work environment and methods. The information relating to categories of the sample and their work experience is reported in Table 3.3.

4.2.3.1. Wearable technology for the work environment and methods of work

When the researcher enquired about construction personnel's understanding and perceived usefulness of WT to the work environment and methods for fatigue detection and interventions, the painter, bricklayers, plumbers, welder, carpenters, cleaners, tiler, and general workers in case project 1 suggested that WT would help notify workers to take rest breaks or to continue working while on site.

> *"With the help of WT, workers would be encouraged to take responsibility for their personal well-being and time management while in the workplace conducting construction tasks",* reiterated the supervisor in case project 1.

The forepersons, quantity surveyor, and estate manager in case project 1 emphasised that WT would help the management to manage workers' time relative to workers' rate of exhaustion in lieu of production rate.

4.2.3.2. Improvement of workers' health using wearable technology

When construction personnel were asked about their perceived effectivess of WT in sleuthing fatigue health and safety risks in the work environment and methods; the storeroom helper, bobcat operator, TLB operator, plumbers, bricklayers, and welders in case project 1 stated that WT would help monitor construction activities and suggesting safe methods of conducting work to ensure that they do not suffer from any illness or fatigue.

The quantity surveyor, forepersons, supervisors, estate manager, tipper truck operator, and roof carpenter in case project 1 highlighted that WT would proactively determine all the health and fatigue risks sources during project undertakings. All RPs in case project 1 agreed to these inferences.

4.2.4. Effectiveness of wearable technology for plant and equipment

This section responded to the fourth objective which endeavoured to evaluate how wearable technology would inform about fatigue related risk factors for plant and equipment operation. The results in this section were categorised into two themes, namely, 'improved plant operating processes' and 'proactive monitoring of plant operators' latent health factors.' These thematic areas responded to the extent to which WT could help inform about fatigue risks and interventions associated with plant and equipment. The RPs composed 14 plant and equipment operators including TLB operators, tipper truck operator, bobcat operator, carpenters, welder, plumbers, and bricklayers to understand how they anticipate WT helping to inform about fatigue risks and possible interventions for plant and equipment operations. The information relating to categories of the sample and their work experience is reported in Table 3.3.

4.2.4.1. Improved plant operating processes

When the RPs were asked about how they anticipate WT helping to inform about fatigue risks and possible interventions for plant and equipment operations, the 2 bricklayers, 2 carpenters, welder, and plumber in case project 1 said that WT would monitor plant operators' air quality, temperature, etc. while operating their tools or plant on site. The 2 TLB operators, bobcat operator, and tipper truck operator in case project 1 mentioned that WT would help establish efficient processes to allow construction companies to save money that would have been spent on operators' medical bills if injured. Moreover, the 2 plumbers and bricklayer in case project 1 stated that WT would foster compliance to improve processes of operating construction plant on construction sites.

4.2.4.2. Proactive monitoring of plant operators' latent health factors

When the RPs were asked about how they anticipate WT helping to inform possible interventions for plant and equipment operations; all plant and equipment operators in case project 1 mentioned that WT aptitude to detect construction operators' internal factors such as lung issues, possible heart attacks while working, and other sicknesses would improve workers' HSW during their operations on site.

> *"WT's ability to monitor plant operators' health and fatigue risks while conducting construction activities would evade H&S risks in real-time on site"*, said the bobcat operator in case project 1.

4.3. Qualitative Case Project 2: Township Development Project

Case study 2 involves a housing development project of a new township in Bloemfontein, Free State province of South Africa. The project covers various construction activities including bulk excavation, levelling, foundations, construction of the first phase of residential buildings, roads and streets, parks, water lines, sewer lines, and electricity lines. This case project was used to collect qualitative data through semi-structured interviews. The research sample for this case study included members of the engineering team. A total of 9 interviews were conducted as indicated in the case sample, refer to Table 3.3.

4.3.1. Best practices for using wearable technology to investigate fatigue risk factors

This section responded to the first research objective which sought to identify the best practices of using wearable technology to leverage data metrics to investigate fatigue related risk areas. The results in this section were categorised into two themes including 'fatigue risks experienced by construction personnel on site' and construction personnel's perception of wearable technology best practices to investigate fatigue'. The RPs composed 9 construction personnel to better understand their fatigue experiences on site and perception of WT. The information relating to categories of the sample and their work experience is reported in Table 3.3. The majority of construction personnel in this case project did not have prior experience of using wearable technology, and some of them had experience and knowledge of WT such as smartwatches for fitness purposes. Therefore, the researcher conducted a presentation on wearable technologies, their uses, advantages and disadvantages, their impact in the medical field and construction projects particularly in the global north, as well as their negative effects on privacy. The purpose of the presentation was to help construction personnel understand wearable technologies and their effectiveness in monitoring various latent factors that could perpetuate health and safety risks on site. As a result, the researcher capitalised on construction personnel's understand of the uses, negative effects, and impact of WT to investigate their perception of WT's effectiveness to monitor fatigue. The main themes that emerged across all RPs in this case project were as follows:

- The construction personnel experienced various mental and physical fatigue risks in this case project.
- The construction personnel believed that WT would help monitor their fatigue risks.
- The construction personnel's new found knowledge of WT gave them confidence that factors such as heart rate, blood pressure, temperature, and activity rate monitoring are best practices of WT and would help track fatigue risks on site.

4.3.1.1. Fatigue risks experienced by construction personnel on site

When the RPs were asked about fatigue risks that were experienced by construction personnel on site; all the construction personnel in case project 2 mentioned that they experienced various kinds of fatigue risks including:

- The construction site is far from the storeroom, causing physical fatigue after walking long distances.
- Conducting construction activities in an environment that is mentally stressful and physically exhaustive.
- The construction personnel were exposed to intense noise and vibration throughout the day, since the project involved heavy plant and equipment.
- Working in an environment that is exposed to ultraviolet rays, causing heat stress.
- Having to worry about work even at home, leading to reduced sleeping period.
- Most of the tasks required construction personnel to exert force, causing exhaustion and sometimes injurying ligaments on a daily bases.
- The construction personnel are sometimes required to work elongated hours conducting repetitive tasks on site, resulting in energy deficience and reduced arletness.

4.3.1.2. Perceived impact of wearable technology to monitor fatigue risks

When asked about the perceived impact of wearable technology to monitor fatigue risks on site, the construction manager and quantity surveyor in case project 2 stated that one of the perceived best practices of WT is its ability to help monitor hidden fatigue levels, tiredness, and latent sickness. Moreover, the TLB operator and grader operator in case project 2 described WT's perceived best practices as its effectiveness in tracking workers' progress on site using smart glasses and smart helmets. The broomer operator in case project 2 perceived WT best practices as its ability to improve workers' health and well-being through appropriate risks monitoring processes during construction activities on site.

> *"Some of us have high blood pressure, therefore we believe WT best practices would include blood pressure, heart rate, movement, and heat or cold rate monitoring when we are working on site"*, said the diesel truck operator in case project 2.

The shuttering specialist and steel fixing specialist in case project 2 pointed out that they perceive the best practices of WT as its ability to track workers' fatigue and heat or cold stress of workers on site.

4.3.2. Wearable technology to evolve early fatigue interventions

This section responded to the second research objective which aimed to describe how the use of wearable technology would help inform about fatigue risk factors to help construction personnel. The results in this section were categorised into two themes, namely, 'WT for early fatigue interventions' and 'proactive monitoring and communication of workers' fatigue risks.' These thematic areas responded to the extent to which WT could help inform about construction personnel's early fatigue and communicate workers' fatigue to the workers concerned and employers timeously. The RPs composed 9 construction personnel to understand the effectiveness of WT in sleuthing workers' early fatigue on site. The information relating to categories of the sample and their work experience is reported in Table 3.3.

4.3.2.1. Wearable technology for early fatigue detection

When the RPs were asked about their peception of wearable technology effectiveness to inform early fatigue interventions , the construction manager and quantity surveyor in case project 2 highlighted that WT would raise awareness about workers' physical and mental health and wellbeing to identify fatigue risks and evolve early fatigue interventions. Correspondingly, the grader operator, TLB operator, smooth drum roller operator, and diesel truck operator in case project 2 mentioned that WT would help improve the work environment to enhance construction personnel's HSW. The steel fixing specialist, broomer operator, and shuttering specialist in case project 2 said that WT would help track factors that cause fatigue to bring about fatigue control measures timeously.

4.3.2.2. roactive monitoring and communication of workers' fatigue

To evolve early fatigue interventions, the quantity surveyor and shuttering specialist in case project 2 mentioned that WT would be used to keep track of how long people work and the conditions in which they work to elude fatigue risks. The smooth drum roller and TLB operator in case project 2 also cited that WT could be used to monitor vital signs such as over-exertion, exhaustion, blood pressure, etc. and address them before causing fatigue risks. The steel fixing specialist and construction manager in case project 2 supported the notion that WT can proactively detect exhaustion and tiredness to allow workers to rest and avoid fatigue. The broomer operator, diesel truck operator, and grader operator in case project 2 alluded that WT would monitor mental stress and exhaustion caused by insufficient rest and sleep and communicate it to construction personnel in real-time to reduce fatigue risk factors.

4.3.3. Effectiveness of wearable technology for the work environment and methods

This section responded to the third research objective which intended to evaluate how wearable technology would inform about fatigue risks and possible interventions for the work environment and methods of work used by construction personnel. The results in this section were categorised into one theme which was 'WT to for the work environment and methods of work.' This thematic area responded to the extent to which workers' behaviour, safety compliance and work demands or activities could be improved using WT to promote workers' HSW in the work environment. The RPs composed 9 construction personnel to understand how they envisage WT helping to inform about fatigue risks and interventions for the work environment and methods. The information relating to categories of the sample and their work experience is reported in Table 3.3.

4.3.3.1. Wearable technology for the work environment and methods of work

When the RPs were asked about how wearable technology would help inform about fatigue risks and possible interventions for the work environment and methods, the construction manager, quantity surveyor, and steel fixing specialist in case project 2 said that sensors could be installed around areas where workers often conduct their daily tasks to monitor their energy and exhaustion levels, allowing them to better take care of themselves.

> *"WT would monitor the health of workers while they are executing tasks to ascertain that they do not die or collapse while working on site"*, elaborated the TLB operator in case project 2.

The broomer operator and smooth drum roller operator in case project 2 highlighted that WT would identify and inform the employer to upgrade some of the processes that cause fatigue in the workplace to ensure workers' HSW. The shuttering specialist and diesel truck operator in case project 2 suggested that WT would help upgrade personal protective equipment (PPE) which will enable PPE equipped with sensors to detect and notify workers when they are exposed to fatigue risks.

> *"WT would track workers' movement and concentration levels when conducting construction activities on site",* stated the grader operator in case project 2.

4.3.4. Effectiveness of wearable technology for plant and equipment

This section responded to the fourth objective which endeavoured to evaluate how wearable technology would inform about fatigue related risk factors for plant and equipment operation. The results in this section were categorised into two themes, namely, 'improved plant operating processes' and 'proactive monitoring of plant operators' latent health factors.' These thematic areas responded to the extent to which WT could help inform about fatigue risks and interventions associated with plant and equipment. The RPs composed 9 plant and equipment operators including TLB operators, tipper truck operator, bobcat operator, bulldozer operator, smooth drum roller operator, broomer operator, and diesel truck operator; to understand how they anticipate WT helping to inform about fatigue risks and possible interventions for plant and equipment operations. The information relating to categories of the sample and their work experience is reported in Table 3.3.

4.3.4.1. Wearable technology for plant and equipment

When the RPs were asked about how they anticipate WT helping to inform about fatigue risks and possible interventions for plant and equipment operations, the quantity surveyor and construction manager in case project 2 intimated that WT would help monitor plant operators' health signals while working on site to avoid fatigue or dizziness. Moreover, the grader operator, steel fixing operator, shuttering operator, and broomer operator in case project 2 highlighted that WT would help monitor elements such as heart rates, blood pressure, and activity rates when installed in plant and equipment, PPE, or directly in plant operators' bodies. Thus, ensuring that plant and equipment operators remain healthy and safe on site.

> *"WT would detect faults and disfunction in plant and equipment such as TLB, to provide real-time interventions"*, retorted the TLB operator in case project 2.

The diesel truck operator in case project 2 stated that WT would help identify risky factors in plant and equipment, thus, fostering employers to implement new strategies for better plant and equipment operations.

4.3.4.2. Proactive monitoring of plant operators' latent health factors

When the RPs were asked about how they anticipate WT helping to inform fatigue interventions for plant and equipment operations, the grader operator and shutting specialist in case project 2 mentioned that WT would help in detecting early fatigue risk factors affecting plant operators on site.

> "*It would also detect various latent elements, depending on the work conducted on site to ensure plant operators' HSW",* reiterated the grader operator in case project 2.

Most construction personnel in case project 2 stated that WT would adapt sensors into every machine, plant, and equipment used on site to increase efficiency on site. The construction manager and quantity surveyor in case project 2 countered that incorporating sensors that could automatically manage time and remind plant operators to take rest breaks would prove effective in sleuthing latent fatigue risk factors.

4.4. Qualitative Case Project 3: Routine Road Maintenance Project

This case study involves a routine road maintenance project located in two South African national roads in Free state province of South Africa. The endeavour encompassed various construction activities including culverts cleaning, earth channel cleaning, edge build-up removal, grass cutting, guardrail repair and installation, traffic accommodation, median cleaning, repair of fencing, road reserves, cleaning of road shoulders, tree felling, and v-drain cleaning. The research sample for this case study included members of the engineering team, contractor, and subcontractors. A total of 12 project participants were interviewed as stipulated in the case sample, refer to Table 3.3.

4.4.1. Best practices for using wearable technology to investigate fatigue risk factors

This section responded to the first research objective which sought to identify the best practices of using wearable technology to leverage data metrics to investigate fatigue related risk areas. The results in this section were categorised into two themes including 'fatigue risks experienced by construction personnel on site' and construction personnel's perception of wearable technology best practices to investigate fatigue'. The RPs composed 12 construction personnel to better understand their fatigue experiences on site and perception of WT. The information relating to categories of the sample and their work experience is reported in Table 3.3. Most construction personnel in this case project had prior experience of using wearable technology such as smartwatches for fitness purposes and casual use, although some of them did not have such experience or knowledge. Therefore, the researcher conducted a presentation on wearable technologies, their uses, advantages and disadvantages, their impact in the medical field and construction projects particularly in the global north, as well as their negative effects on privacy. The purpose of the presentation was to help construction personnel understand wearable technologies and their effectiveness in monitoring various latent factors that could perpetuate health and safety risks on site. As a result, the researcher capitalised on construction personnel's understand of the uses, negative effects, and impact of WT to investigate their perception of WT's effectiveness to monitor fatigue. The main themes that emerged across all RPs in this case project were as follows:

- The construction personnel experienced various mental and physical fatigue risks in this case project.
- The construction personnel believed that WT would help monitor their fatigue risks.
- The construction personnel's experience of using smartwatches gave them confidence that factors such as heart rate, blood pressure, temperature, and activity rate monitoring are best practices of WT and would help monitor fatigue risks on site.

4.4.1.1. Fatigue risks experienced by construction personnel on site

When the RPs were asked about fatigue risks that were experienced by construction personnel on site; all the construction personnel in case project 3 mentioned that they experienced various kinds of fatigue risks including:

- The construction site is far from the storeroom, causing physical fatigue after walking long distances.
- Conducting construction activities in an environment that is mentally stressful and physically exhaustive.
- The construction personnel were exposed to intense noise and vibration throughout the day, since the project involved heavy plant and equipment.
- Working in an environment that is exposed to ultraviolet rays, causing heat stress.
- Having to worry about work even at home, leading to reduced sleeping period.
- Most of the tasks required construction personnel to exert force, causing exhaustion and sometimes injurying ligaments on a daily bases.
- The construction personnel are sometimes required to work elongated hours conducting repetitive tasks on site, resulting in energy deficience and reduced arletness.

4.4.1.2. Perceived impact of wearable technology to monitor fatigue risks

When asked about the perceived impact of wearable technology to monitor fatigue risks on site, the director and foreperson of the grass cutting subcontractor in case project 3 perceived WT useful since it can monitor workers' temperature and blood pressure. The 2 forepersons and the drum roller operator in case project 3 alluded that the best practices of WT known to them encompass its ability to track construction workers' fatigue, location, and progress on site. The driver in case project 3 perceived WT's best practices as its ability to help workers and employers remain alert and aware of their work environment and methods of work while conducting construction tasks on the road. The 3 brush cutter operators and general worker in case project 3 stated that WT's best practices include monitoring of fatigue and concentration using smart glasses, which they can also use as goggles against grass and stone particles during grass cutting on site.

4.4.2. Wearable technology to evolve early fatigue interventions

This section responded to the second research objective which aimed to describe how the use of wearable technology would help inform about fatigue risk factors to help construction personnel. The results in this section were categorised into two themes, namely, 'WT for early fatigue interventions' and 'proactive monitoring of health factors to reduce fatigue.' These thematic areas responded to the extent to which WT could help inform about construction personnel's early fatigue and communicate workers' fatigue to the workers concerned and employers timeously. The RPs composed 12 construction personnel to understand the effectiveness of WT in sleuthing workers' early fatigue on site. The information relating to categories of the sample and their work experience is reported in Table 3.3.

4.4.2.1. Wearable technology for early fatigue interventions

When the RPs were asked about their peception of wearable technology effectiveness to inform early fatigue interventions, the drum roller operator in case project 3 mentioned that WT could inform workers to rest for scheduled times to avoid exhaustion. The brush cutter operators in case project 3 added, saying that it could also reduce overexertion and detect possible fatigue risks timely to prevent harm, injury, or fatality to workers. More telling is the statement made by one of the forepersons, supervisor, and director in case project 3, indicating that WT could evolve fatigue risk interventions by proactively detecting latent health factors that might be detrimental to workers wellbeing.

> *"WT could inform workers about their heart rates, BP, etc. to evade fatigue risks or workers collapsing on the job site"*, remarked the driver in case project 3 when asked about how WT would evolve early fatigue interventions to help construction personnel.

The general workers also highlighted that WT would alert workers of any threats to H&S during construction undertakings.

4.4.2.2. Proactive monitoring of health factors to reduce fatigue

When asked about how wearable technology would evolve early fatigue risks interventions to help construction personnel, the general workers in case project 3 said that elements such as high blood pressure and heart rate could be monitored using WT to ensure that workers are aware of their limitations while conducting construction activities.

"WT would help monitor factors such as heart rate, blood pressure, hunger, dizziness, and stress levels to addressed fatigue", elaborated the brush cutter operator in case project 3.

The supervisor, driver and forepersons in case project 3 alluded that WT could monitor brain activity, visual cues, and microsleeps in real-time to dodge fatigue's negative effects. The director and drum roller operator in case project 3 underscored that WT would give workers early warning signs such as sleep apnea, feeling sick, disorientation, anxiety, stress, losing balance while walking, and sometimes experiencing pain to ligaments and muscles; which would help avoid injuries and fatigue risks during construction activities.

4.4.3. Effectiveness of wearable technology for the work environment and methods

This section responded to the third research objective which intended to evaluate how wearable technology would inform about fatigue risks and possible interventions for the work environment and methods of work used by construction personnel. The results in this section were categorised into one theme, namely, 'proactive and constant monitoring and training.' This thematic area responded to the extent to which workers' behaviour, safety compliance, and work demands or activities could be improved using WT to promote workers' HSW in the work environment. The RPs composed 12 construction personnel to understand how they envisage WT helping to inform about fatigue risks and interventions for the work environment and methods. The information relating to categories of the sample and their work experience is reported in Table 3.3.

4.4.3.1. Proactive and constant monitoring and training

When the RPs were asked about how wearable technology would help inform about fatigue risks and possible interventions for the work environment and methods; the foreperson in case project 3 enunciated that installing various sensors on site, equipment used, and machinery would proactively inform about health and fatigue risks during construction activities on site to improve the work environment and methods. Furthermore, one of the supervisors in case project 3 suggested that installing sensors in workers' PPE to constantly monitor and track workers' functionality on site would inform about fatigue risks.

"WT's latent health detecting abilities would help ensure a healthy workforce, which would in turn provide a safe work environment, balanced work progress, and keep all the workers aware of their HSW", reiterated the driver in case project 3.

A foreperson in case project 3 highlighted that training and awareness about WT as well as workers' physical and mental H&S would inform about possible fatigue risks interventions for the work environment and methods.

"WT would inform detecting the levels of vibration and comfortability emanating from the workplace and work methods. This would allow the employer to improve the work

environment and methods before they cause fatigue", suggested the brush cutter operator in case project 3.

The drum roller operator in case project 3 also mentioned that monitoring epochs such as workers' heart rates to diagnose stress and fatigue using WT would help improve construction personnel's health and safety at work.

4.4.4. Effectiveness of wearable technology for plant and equipment

This section responded to the fourth objective which endeavoured to evaluate how wearable technology would inform about fatigue related risk factors for plant and equipment operation. The results in this section were categorised into two themes, namely, 'incorporating WT in plant and equipment' and 'proactive detection of latent fatigue risks.' These thematic areas responded to the extent to which WT could help inform about fatigue risks and interventions associated with plant and equipment. The RPs composed 5 construction plant and equipment operators including the smooth drum roller operator, driver, and 3 brush cutter operators; to understand how they anticipate WT helping to inform about fatigue risks and possible interventions for plant and equipment operations. The information relating to categories of the sample and their work experience is reported in Table 3.3.

4.4.4.1. Incorporating wearable technology in plant and equipment

When the RPs were asked about how they anticipate WT helping to inform about fatigue risks and possible interventions for plant and equipment operations, the drum roller operator in case project 3 remarked that WT would incorporate devices or sensors to plant and operators' PPE to detect risky exertion that would lead to fatigue.

> *"WT would adapt sensors in operators' PPE to notify them when working in awkward postures, thus, mitigating musculoskeletal disorders and fatigue"*, stressed the brush cutter operator in case project 3.

> *"Technology imbedded in plant or equipment would improve productivity since plant operators would be aware of fatigue risk factors, thus, working efficiently and using safe work procedures"*, reiterated one of the brush cutter operators in case project 3.

The driver in case project 3 retorted that WT would help regulate good air and temperature in plant or equipment to ensure that operators work comfortably without fatigue risks that would make them prone to causing accidents.

4.4.4.2. Proactive detection of latent fatigue risks

When the RPs were asked about how they anticipate WT helping to inform fatigue risk interventions for plant and equipment operations, one of the brush cutter operators in case project 3 pointed out that WT would inform workers when they are overworked or using wrong operating methods when operating machines.

"Technological advancements in plant and equipment with the ability to adjust plant's safety belts by sensing the size of the operator. The sensors would also monitor machines' comfortability, air quality, noise levels, and vibration levels to inform the operator to wear relevant PPE. This would minimise health risks and fatigue", explained the drum roller operator in case project 3.

The driver in case project 3 noted that plant and equipment equipped with WT fixtures such as sleep vibrator and concentration alert would enable plant operators to work effectively without losing concentration or sleeping while operating to avoid accidents and injuries.

4.5. Quantitative Data: Survey Questionnaires

This study utilized the SPSS software to compute and analyse descriptive statistics to support the interview data collected from three case projects in Bloemfontein, Free State province of South Africa. The statistical data were collected from 116 construction personnel including professionals registered with counsils such as SACPCMP, ECSA, and SACAP; site agents; junior quantity surveyors; candidate architects; supervisors; forepersons; artisans; plant operators; and general workers in Bloemfontein, Free State province of South Africa. The survey questions were predicated on a Likert scale of one (1) to five (5); with 1 = Poor, 2 = Fair, 3 = Good, 4 = Very Good, 5 = Excellent. The Likert scale also incorporated the unsure (0) option. The quantitative data were analysed using IBM SPSS Statistics version 29.0.1.1 to derive the mean scores and standard deviation of each research variable relating to fatigue and WT.

4.5.1. Response Rate

One hundred and twenty (120) survey questionnaires were administered to construction personnel in the construction industry to validate the qualitative data collected through semi-structured interviews. At the end of the survey period that spanned 16 weeks, 116 valid responses were received, which equated to 97% response rate. The researcher achieved this response rate by administering hard copies to the research sample, followed by constant reminders and organised collection dates of survey responses.

4.5.2. Demographic Information

4.5.2.1. Gender

Table 4.1 displays the RPs' gender differences. The statistical dataset of this research involved 79% male and 21% female participants. The data implied that male construction personnel's views were predominant in this study.

Table 4.1: Research participants' gender

Variable		N	(%)
Gender	Male	92	79.0
	Female	24	21.0

Total	116	100.0

4.5.2.2. Age Group

Table 4.2 presents the age groups that participated in this research. The results shows that construction personnel between the ages 30-39 greatly contributed 40% to this study followed by ages 20-29 at 28%. Ages 40-49 came third at 26%, then, construction personnel with 50+ years of age contributed 6% of the total response rate.

Table 4.2: Research participants' age

Variable		N	(%)
Age	20 – 29 years	33	28.0
	30 – 39 years	46	40.0
	40 – 49 years	30	26.0
	50+ years	7	6.0
Total		**116**	**100.0**

4.5.2.3. Work Experience

Table 4.3 displays RPs' work experience in the construction industry. Forty-nine (49%) of participants had 0-5 years of experience, 29% of participants had 6-10 years of experience, 12% of participants had 11-15 years of experience, and 10% of participants had over 16 years of experience in construction endeavours. Therefore, participants with over 6 years of experience contributed 51%.

Table 4.3: Research participants' work experience

Variable		N	(%)
Years in the current position	0 – 5 years	57	49.0
	6 – 10 years.	34	29.0
	11 – 15 years.	14	12.0
	16+ years.	11	10.0
Total		**116**	**100.0**

4.5.2.4. Level of Education

Table 4.4 presents the education levels of construction personnel who participated in this research. The results indicated that a high percentage (48%) of workers had diplomas and bachelor's degrees. 32% of participants had matric and below. 10% of workers completed their postgraduate studies. Another 10% had college certificates. There were no participants who completed their doctoral qualifications.

Table 4.4: Research participants' education level

Variable	N	(%)

Qualification	Below Matric & Matric	37	32.0
	College Certificate	12	10.0
	Undergraduate	56	48.0
	Postgraduate	11	10.0
Total		**116**	**100.0**

4.5.2.5. Job Title or Position

Table 4.5 presents RPs' roles in construction. The results show that the highest percentage (41%) of participants were construction managers, quantity surveyors, and site agents who were not registered with any professional counsil, followed by 20% of participants that were registered with recognised professional counsils including SACPCMP, SACQSP, SACAP, ECSA, etc. 32% of participants were artisans, 5% were plant operators, and 2% were general workers, demonstrating the daily on-site experience of construction personnel.

Table 4.5: Research participants' job roles

	Variable	**N**	**(%)**
Designation	Professionals/Consultants	23	20.0
	Artisans	37	32.0
	Plant Operators	6	5.0
	General Workers	2	2.0
	Managers	48	41.0
Total		**116**	**100.0**

4.5.2.6. Type of Project

Table 4.6 presents the type of projects RPs were involved in. Most participants were involved in residential building (56%) and industrial/engineering (30%) projects. 11% of participants were involved in institutional building projects and 3% in commercial building projects. The results indicate that RPs were involved in residential, industrial, institutional, and commercial building projects; thus, the results reflect different project experiences.

Table 4.6: Research participants' project endeavours

	Variable	**N**	**(%)**
Project Type	Residential Building	65	56.0
	Commercial Building	3	3.0
	Industrial/Civil Works	35	30.0
	Institutional Building	13	11.0
Total		**116**	**100.0**

4.5.3. Quantitative Data Analysis

The research statistical data analysed the measure of central tendency and measure of central variability for all research variables. This was done to evaluate the level of agreement between different construction personnel to better understand fatigue effects and WT best practices acceptable to RPs. The survey questions were predicated on a Likert scale of one (1) to five (5); with 1 = Poor, 2 = Fair, 3 = Good, 4 = Very Good, 5 = Excellent. The Likert scale also incorporated the unsure (0) option. The quantitative data were analysed using IBM SPSS Statistics version 29.0.1.1 to derive the mean scores and standard deviation of each research variable relating to fatigue and WT.

The rationale for not including the frequency or relative frequency of variables pursuant to the predetermined Likert Scale was influenced by the central research question which asks, how can a WT protocol assist in the reduction of fatigue risk factors on construction sites? In this section, the researcher endeavoured to understand construction personnel's perception of the effectiveness of WT in sleuthing fatigue risks, and the remarks in the data aimed to assess the acceptance or rejection of the fatigue and WT factors by allowing RPs to rate each research variable or construct. The variables and constructs that were rated 0.0 to 2.5 were classified as rejected and factors rated 3.0 and above were deemed accepted by RPs. In the same breath, the researcher aimed to uncover the nature of fatigue risks that construction personnel are exposed to and how they perceive the usefulness of WT in monitoring such risks. These results were later adopted in the development of a WT protocol to reduce fatigue risk factors on construction sites.

The reliability of data obtained from survey questionnaire instrument was established using Cronbach's Alpha measurement to demonstrate the data internal consistency. Table 3.7 presents the Cronbach's Alpha rule of thumb that was used to interpret the internal consistency of the quantitative data in this study. The Cronbach's Alpha was used to assess how well a set of variables and constructs measured the same underlying factors. The variables and constructs were considered 'reliable yet questionable' when the Cronbach's Alpha score was equal or greater than 0.6, 'acceptable' when it was greater or equal to 0.7, 'good' when it was greater or equal to 0.8, and 'excellent' when it is greater or equal to 0.9. The survey respondents composed construction personnel registered with professional councils including SACPCMP, SACQSP,SACAP, ECSA, etc, unregistered construction managers, quantity surveyors, site agents, artisans, forepersons, plant operators, and general workers. The validity of survey questionnaire instrument was measured by assessing the alignment of research variables and constructs with research objectives.

The quantitative results were discussed using four (4) research objectives as subdivisions. The research objectives included the following:

- Identify the best practices of using wearable technology to leverage data metrics to investigate fatigue risk factors.
- Describe how to use wearable technology to evolve early fatigue interventions to help construction personnel.
- Evaluate how wearable technology would inform about fatigue risk factors for the work environment and methods of work.
- Evaluate how wearable technology would inform about fatigue risk factors for plant and equipment operation.

4.5.3.1. Best practices for using wearable technology to monitor fatigue risk factors

This subdivision responded to the first objective which sought to identify the best practices of using wearable technology to leverage data metrics to investigate fatigue related risk areas. To achieve this objective, the statistical data was divided into two categories: workers' exposure to fatigue risk factors and perceived effectiveness of WT key practices.

Workers' exposure to fatigue risk factors

Using a scale of 1 – 5 (1 being very low and 5 very high), RPs were asked to rate the extent to which they are exposed to the risk factors in Table 4.7. The Likert scale incorporated the unsure (0) option within the scale 1 = Very Low, 2 = Below Average, 3 = Average, 4 = Above Average, 5 = Very High.

The RPs were asked to rate the extent to which they are exposed to fatigue risk factors akin to mental exhaustion, physical exhaustion, stressful work environment, repetitive tasks, sleep deprivation, blind spots, proximity within the work environment, intense ultraviolet rays causing heat stress, materials located far from the work site, and confined work areas resulting in awkward postures. This question allowed the RPs to rate nine variables which were extracted from the reviewed literature in Figure 2.1 and Table 2.4. The results in Table 4.7 indicated that the RPs experienced fatigue risk factors in their construction workplaces since the MSs of all 9 risk factors were above the midpoint of 2.50. The RPs ranked 'exposure to stressful work environment' high with an MS of 4.69 and 'conducting tasks in confined work areas resulting in awkward posture' lower with an MS of 3.81.

Table: 4.7: Exposure to risk factors

Risk factor	MS	Std.	Rank	Remarks
Exposure to stressful work environment.	4.69	0.654	1	Accepted
Exposure to mental and physical exhaustion at work.	4.54	0.679	2	Accepted

Exposure to repetitive tasks.	4.63	0.798	3	Accepted
Poor housekeeping within the work environment.	3.74	0.947	4	Accepted
Exposure to intense ultraviolet rays causing heat stress.	3.86	0.963	5	Accepted
Conducting tasks with limited visibility (blind spots)	3.45	1.019	6	Accepted
Often Sleep less than seven hours.	4.28	1.022	7	Accepted
Materials located far from the work site.	3.72	1.105	8	Accepted
Conducting tasks in confined work areas resulting in awkward postures.	3.81	1.154	9	Accepted

To measure the reliability of the statistical dataset, Cronbach's alpha coefficient was used as shown in Table 4.8. Based on 9 standardized items, the Cronbach's alpha internal consistency was 0.86. The results indicate that the Cronbach's Alpha internal consistency is good and reliable since it surpasses the acceptible value of 0.7 and is within the standardized zero to one scale.

Table 4.8: Reliability of statistical data

Reliability Statistics		
Cronbach's Alpha	Cronbach's Alpha Based on Standardized Items	N of Items
0.864	**0.862**	9

Perceived effectiveness of wearable technology key practices

Using a scale of 1 – 5 (1 being Poor and 5 being Excellent), RPs were required to rate predetermined indicators for using wearable technology to leverage data metrics to investigate fatigue risk factors. These indicators were extracted from literature reviewed in this research and aligns with the main research objectives as indicated in Table 3.2. The Likert scale incorporated the unsure (0) option within the scale 1 = Poor, 2= Fair, 3 = Good, 4 = Very Good, 5 = Excellent.

Table 4.9 shows construction personnel' perceived effectiveness of key practices or indicators to detect fatigue using WT. The statistical data was collected from the RPs working in the construction industry within the Free State province of South Africa. The RPs included construction managers, quantity surveyors, and site agents who were not registered with any professional counsil, construction personnel registered with recognised professional counsils including SACPCMP, SACQSP, SACAP, ECSA, etc., forepersons, supervisors, plant operators, artisans, and general workers as indicated in Table 3.4. The first question endeavoured to determine the RPs' perceived effectiveness of WT key practices by allowing them to rate eighteen (18) variables which were extracted from the reviewed literature in Table 2.1. The Mean Scores (MS) of the 18 WT best practices for fatigue risks monitoring were above the midpoint of 2.50, indicating that these indicators were accepted and deemed effective to monitor workers' fatigue in construction sites. For instance, the RPs ranked ‘the ability of WT to monitor brain activity rate’ first with an MS of 4.83 and ‘WT would monitor and help workers regulate their energy levels’ last with an MS of 4.36.

Table: 4.9: Best practices for using wearable technology to monitor fatigue risks

Variables	MS	Std.	Rank	Remarks
WT is eefctive in monitoring brain activity rate.	4.83	0.423	1	Accepted
WT would detect blood pressure.	4.76	0.450	2	Accepted
WT would monitor body and skin temperature.	4.76	0.487	3	Accepted
WT would detect heart rate.	4.73	0.482	4	Accepted
WT would help monitor human pulse wave.	4.78	0.495	5	Accepted
WT would effectively indicate if the worker is experiencing Heat stress.	4.72	0.504	6	Accepted
WT would track human motion on site.	4.76	0.504	7	Accepted
WT would show clear human physiological fatigue signals.	4.76	0.504	8	Accepted
WT would track workers’ location.	4.75	0.509	9	Accepted
WT would monitor workers’ muscle activity rate.	4.78	0.512	10	Accepted
WT would monitor workers’ oxygen saturation levels.	4.62	0.554	11	Accepted
WT would allow the detection of any decline in workers’ energy levels.	4.66	0.574	12	Accepted
WT would monitor blood oxygen saturation levels.	4.68	0.584	13	Accepted
WT would monitor workers’ respiration rate.	4.69	0.596	14	Accepted

WT would monitor heart rate variability (HRV).	4.57	0.608	15	Accepted
WT would proactively provide fall alert for the workers on site.	4.43	0.662	16	Accepted
WT would assist construction personnel with pressure imaging in real-time.	4.56	0.726	17	Accepted
WT would help workers regulate their energy levels.	4.36	1.145	18	Accepted

To measure the reliability of the statistical dataset, Cronbach's alpha coefficient was used as shown in Table 4.10. Based on 18 variables, the Cronbach's alpha coefficient was 0.90. The results indicate that the Cronbach's Alpha internal consistency is excellent and reliable since it surpasses the acceptable value of 0.7 and is within the standardized zero to one scale.

Table 4.10: Reliability of statistical data

Reliability Statistics		
Cronbach's Alpha	Cronbach's Alpha Based on Standardized Items	N of Items
0.888	**0.901**	18

4.5.3.2. Wearable technology to evolve early fatigue interventions

This subdivision responded to the second research objective which endeavoured to describe how to use wearable technology to evolve early fatigue interventions to help construction personnel. To achieve this objective, the statistical data was divided into three categories: types of fatigue experienced by workers on site, frequency of exposure to physical risk factors, and WT monitoring purposes.

Types of fatigue experienced by workers on site

Using a scale of 1 (Never) to 5 (Always), RPs were asked to rate the extent to which they experience the types of fatigue indicated in Table 4.11. The Likert scale incorporated the unsure (0) option within the scale 1 = Never, 2 = Rarely, 3 = Sometimes, 4 = Very Often, 5 = Always.

Table 4:11 shows construction personnel' fatigue experiences when working on site to understand the types of WT needed for fatigue risk reduction. The statistical data was collected from the RPs working in the construction industry within the Free State province of South Africa. The RPs included professional, managers, forepersons, supervisors, plant operators, artisans, and general workers as indicated in Table 3.4. A Likert scale of 1 to 5 was adopted for the survey questions and analysed using IBM SPSS Statistics version 29.0.1.1. The results imply that construction personnel are susceptible to physical and mental fatigue as shown in Table 4:11. The research participant ranked two variables including physical fatigue and mental fatigue which were extracted from the reviewed literature in Figure 2.1 and Figure 2.2. The MSs of the two types of fatigue experienced by construction personnel were above the midpoint of 2.50, indicating that construction personnel experience both physical and mental fatigue when undertaking construction tasks. The RPs ranked 'physical fatigue' high with an MS of 4.71 and 'mental fatigue' low with an MS of 4.41.

Table: 4.11: Types of fatigue experienced by workers on site

Fatigue aspects	**MS**	**Std.**	**Rank**	**Remarks**
Physical fatigue	4.71	0.685	1	Accepted
Mental fatigue	4.41	0.803	2	Accepted

To measure the reliability of the statistical dataset, the Cronbach's Alpha coefficient was used as shown in Table 4.12. Based on 2 standardized items, the Cronbach's Alpha coefficient was 0.30. The results indicate that the Cronbach's Alpha internal consistency is unacceptable and unreliable since it is below the accaptible value of 0.7.

Table 4.12: Reliability of statistical data

Reliability Statistics		
Cronbach's Alpha	Cronbach's Alpha Based on Standardized Items	N of Items
0.295	**0.298**	2

Frequency of exposure to physical risk factors

Using a scale of 1 – 5 (1 being Never and 5 being Always), RPs were asked to rate the frequency to which their work exposes them to risk factors indicated in Table 4.13 while executing construction tasks on site. The Likert scale incorporated the unsure (0) option within the scale 1 = Never, 2 = Rarely, 3 = Sometimes, 4 = Very Often, 5 = Always.

The physical risk factors included forceful exertion, static load, repetitive motion, bending, twisting movement, awkward posture, energy deficiency, reduced alertness, and material handling loads which construction personnel are often exposed to according to Table 4.13. The research participant rated eight (8) constructs or variables which were extracted from the reviewed literature in Figure 2.3. The MSs of all 8 physical risk factors were above the midpoint of 2.50, implying that construction personnel were exposed to various physical loads perpetuating fatigue risk factors on site. For instance, the RPs ranked 'bending and twisting movement' first with an MS of 4.26 and 'static load' last with an MS of 3.22.

Table: 4.13: Physical load exposure during construction activities

Aspects	**MS**	**Std.**	**Rank**	**Remarks**
Exposure to bending & twisting movement	4.26	0.796	1	Accepted

Exposure to awkward posture	4.20	0.929	2	Accepted
Exposure to repetitive motion	4.20	0.900	3	Accepted
Often experience energy deficiency	3.81	1.034	4	Accepted
Often experience reduced alertness	3.67	0.896	5	Accepted
Exposure to forceful exertion	3.36	1.102	6	Accepted
Often involved in material handling	3.33	1.212	7	Accepted
Exposure to carrying load throughout my work shift.	3.22	0.998	8	Accepted

To measure the reliability of the statistical dataset, Cronbach's alpha coefficient was used as shown in Table 4.14. Based on 8 standardized items, the Cronbach's alpha coefficient was 0.93. The results indicate that the Cronbach's Alpha internal consistency is excellent and reliable since it surpasses the acceptible value of 0.7 and is within the standardized zero to one scale.

Table 4.14: Reliability of statistical data

Reliability Statistics		
Cronbach's Alpha	Cronbach's Alpha Based on Standardized Items	N of Items
0.925	**0.930**	8

Wearable technology monitoring purposes

Using a scale of 1 – 5 (1 being Definitely Not and 5 being Definitely), RPs were asked to rate the WT monitoring purposes to reduce fatigue risk factors on construction sites. The Likert scale incorporated the unsure (0) option within the scale 1 = Definitely Not, 2 = Probably Not, 3 = Possibly, 4 = Probably, 5 = Definitely.

Table 4.15 presents statistical results relating to WT monitoring purposes including the belt device to detect high-risk bending, twisting, and reaching; smart glasses to monitor the drivers and plant operators' fatigue. The chest harness for real-time measurement of vitals, knowledge of location, health status, and manage safety, patch for real-time reports of heat stress indicators, worksite heat assessment, training, and consultation. Wrists monitor for hand-arm vibration (HAV) risk assessment, tool testing, exposure monitoring, and risk control appraisal; safety button for sending alerts and location data, press unique buttons for non-emergency or emergency response; clip for fall alerts, self-alerts, and logging. Gloves to strengthen gripping and grasping action, adjust applied force, and balance between fingers; exoskeleton to distribute upper body weight, reduce fatigue, and muscle stress. Flexible band to measure fatigue and alertness at real-time, eliminate microsleeps, and support wellness; as well as shoes to measure gait changes, impact, and fatigue as indicated in Table 4.15.

The RPs rated fourteen (14) variables which were extracted from the reviewed literature in Table 2.5, Table 2.6, and Table 2.7. The MSs of the 14 WT monitoring purposes were above the midpoint of 2.50, implying that construction personnel support and accept these monitoring purposes as effective in sleuthing fatigue risk factors in construction. The RPs ranked 'smart glasses to monitor the drivers and plant operators' fatigue' high with an MS of 4.86 and 'exoskeleton to distribute upper body weight, reduce fatigue, and muscle stress' low with an MS of 4.47.

Table: 4.15: Wearable technology monitoring purposes

Variables	MS	Std.	Rank	Remarks
Smart glasses to monitor the drivers and plant operators' fatigue.	4.86	0.435	1	Accepted
Chest device for mobile human monitoring; 24/7 H&S observations in extreme environments	4.84	0.429	2	Accepted
Belt device to detect high-risk bending, twisting, and reaching	4.83	0.594	3	Accepted
Clip for fall alerts; self-alerts, and logging	4.83	0.481	4	Accepted
Chest harness for real-time measurement of vitals; knowledge of location and health status; manage safety	4.82	0.486	5	Accepted
Patch for real-time reports of heat stress indicators; worksite heat assessment; training and consultation	4.82	0.468	6	Accepted
Chest device to track body vitals, biomechanical metrics, and physical load monitoring	4.80	0.479	7	Accepted
Wrists monitor for hand-arm vibration (HAV) risk assessment; tool testing; exposure monitoring; risk control appraisal	4.78	0.620	8	Accepted
Safety button for sending alerts and location data, press unique buttons for non-emergency or emergency response	4.78	0.512	9	Accepted

Belt for collecting data on location, activity, and environment; identification of risky activities; haptic response	4.76	0.569	10	Accepted
Flexible band to measure fatigue and alertness at real-time; eliminate microsleeps; support wellness	4.75	0.644	11	Accepted
Gloves to strengthen gripping and grasping action; adjust applied force and balance between fingers	4.75	0.617	12	Accepted
Shoes to measure gait changes, impact, and fatigue	4.70	0.662	13	Accepted
Exoskeleton to distribute upper body weight; reduce fatigue and muscle stress	4.47	0.652	14	Accepted

To measure the reliability of the statistical dataset, the Cronbach's Alpha coefficient was used as shown in Table 4.16. Based on 14 standardized items, the Cronbach's Alpha coefficient was 0.93. The results indicate that the Cronbach's Alpha internal consistency is excellent and reliable since it surpasses the acceptable value of 0.7 and is within the standardized zero to one scale.

Table 4.16: Reliability of statistical data

Reliability Statistics		
Cronbach's Alpha	Cronbach's Alpha Based on Standardized Items	N of Items
0.924	**0.931**	14

4.5.3.3. Wearable technology to redesign the work environment and methods to reduce fatigue

This subdivision responded to the third research objective which purposed to evaluate how wearable technology would inform about fatigue risks and possible interventions for the work environment and methods of work used by construction personnel. To achieve this objective, the statistical data was divided into one category: mental fatigue exposure during construction activities

Mental fatigue exposure during construction activities

Using a scale of 1 – 5 (1 being never and 5 being always), RPs were asked to rate the frequency to which they experience fatigue risk factors in Table 4.17 while working on site. The Likert scale incorporated the unsure (0) option within the scale 1 = Never, 2 = Rarely, 3 = Sometimes, 4 = Very Often, 5 = Always.

Table 4.17 shows construction personnel's cognitive fatigue experience in the workplace and when undertaking construction tasks. The survey results highlighted that construction personnel experienced fatigue risks in various forms. Sometimes fatigue emanates from tiredness/exhaustion, lack of sleep, irritation, work stress, work that requires concentration, headaches, and heat or cold stress. The RPs rated seven (7) constructs which were extracted from the reviewed literature in Table 2.2 and Table 2.3. The MSs for 6 of the 7 fatigue risk factors were above the midpoint of 2.50

and only one risk factor below the 2.50 midpoint, evincing that construction personnel were often exposed to mental risk factors including tiredness/exhaustion, sleepy, irritation, work stress, reduced focus, headaches, and heat or cold stress as demonstrated in Table 4.17. The RPs ranked 'tiredness/exhaustion' high with an MS of 4.56 and 'irritation' low with an MS of 2.97.

Table: 4.17: Mental fatigue exposure during construction activities

Factors	MS	Std.	Rank	Remarks
Mostly tired/exhausted at work.	4.56	0.650	1	Accepted
Usually stressed by job tasks.	4.13	0.764	2	Accepted
Often experience reduced focus.	3.70	0.962	3	Accepted
Usually exposed to heat/cold stress.	3.45	0.990	4	Accepted
Often experience headaches while working.	3.30	0.857	5	Accepted
Usually feel sleepy while conducting tasks.	3.22	0.967	6	Accepted
Easily irritated by activities or people at work.	2.97	0.874	7	Rejected

To measure the reliability of the statistical dataset, the Cronbach's Alpha coefficient was used as shown in Table 4.18. Based on 7 standardized items, the Cronbach's Alpha coefficient was 0.80. The results indicate that the Cronbach's Alpha internal consistency is good and reliable since it surpasses the acceptable value of 0.7 and is within the standardized zero to one scale.

Table 4.18: Reliability of statistical data

Reliability Statistics		
Cronbach's Alpha	Cronbach's Alpha Based on Standardized Items	N of Items
0.800	**0.800**	7

4.5.3.4. Wearable technology to redesign plant and equipment to reduce fatigue

This subdivision responded to the fourth research objective which endeavoured to evaluate how wearable technology would inform about fatigue related risk factors for plant and equipment operation. To achieve this objective, the statistical data was divided into two categories: plant and equipment operators on site and environmental loads experienced by plant operators on site.

Plant and equipment operators on site

Using a scale of 1 (Never) – 5 (Always), RPs were asked to rate the extent to which they operate the types of construction plant or equipment mentioned in Table 4.19. The Likert scale incorporated the unsure (0) option within the scale 1 = Never, 2 = Rarely, 3 = Sometimes, 4 = Very Often, 5 = Always.

The RPs rated eleven (11) constructs which were influenced by the reviewed literature in chapter 2. The results in Table 4.19 indicate that plant operators are not involved with every machine on site, but operate specific machines. For example, only a few plant operators were operating construction plant such as cranes, concrete trucks, forklifts, earthmovers, tipper trucks, and soil compactors. While most construction personnel were operating equipment such as Hand drills, hand grinders, nail guns, and generators. The high rate of equipment usage by operators could be a result of various artisans using these equipment. While plant operation is a specialised field requiring thorough training and certification and only a few plants were available on site. Hence, the MSs of 9 out of 11 variables were below the midpoint of 2.50 with only 2 variables having MSs that surpass the midpoint of 2.50. The RPs ranked the 'generator' as the most used construction equipment with an MS of 3.75 and the 'concrete plant' as the least operated construction plant with an MS of 1.08.

Table: 4.19: Plant and equipment operators on site

Plant & Equipment	MS	Std.	Rank	Remarks
Generator	3.75	1.461	1	Accepted
Hand grinder	3.50	1.540	2	Accepted
Nail gun	2.94	1.620	3	Rejected
Hand drill	2.83	1.665	4	Rejected
Soil compaction machine	1.86	1.246	5	Rejected
Trucks	1.56	1.157	6	Rejected
Earthmoving plant	1.50	1.134	7	Rejected
Excavator	1.28	0.882	8	Rejected
Forklift	1.19	0.710	9	Rejected
Crane	1.11	0.523	10	Rejected
Concrete plant	1.08	0.500	11	Rejected

To measure the reliability of the statistical dataset, the Cronbach's Alpha coefficient was used as shown in Table 4.20. Based on 11 standardized items, the Cronbach's Alpha coefficient was 0.63. The results indicate that the Cronbach's Alpha internal consistency is questionable since it is below the acceptable value of 0.7.

Table 4.20: Reliability of statistical data

Reliability Statistics		
Cronbach's Alpha	Cronbach's Alpha Based on Standardized Items	N of Items
0.479	**0.632**	11

Environmental loads experienced by plant operators on site

Using a scale of 1 – 5 (1 being Never and 5 being Always), RPs were asked to rate the frequency to which they experience the fatigue risk factors in Table 4.21 while operating plant and equipment on site. The Likert scale incorporated the unsure (0) option within the scale 1 = Never, 2 = Rarely, 3 = Sometimes, 4 = Very Often, 5 = Always.

The results in Table 4.21 highlights the effects of plant to construction personnel on site. Although operators and workers on site do not operate every plant and equipment, they are affected in different ways. For instance, most workers and plant operators experienced environmental loads including noise, vibration, cold and heat stress, etc. caused by plant and equipment during construction undertakings. The RPs rated eight (8) constructs or variables which were extracted from the reviewed literature in Figure 2.1 and Table 2.3. The MSs of all the 8 environmental loads were above the midpoint of 2.50, indicating that these loads affect many construction personnel not just the plant operators. The RPs ranked ‘exposure to repetitive work’ high with an MS of 4.64 and ‘exposure to humidity’ low with an MS of 4.03.

Table: 4.21: Environmental loads experienced by plant operators

Environmental Load	**MS**	**Std.**	**Rank**	**Remarks**
Exposure to repetitive tasks.	4.64	0.487	1	Accepted
Exposure to twisting and bending when conducting activities on site.	4.61	0.494	2	Accepted
Often move my body awkwardly.	4.50	0.507	3	Accepted
Often experience exhaustion due to the sun’s heat.	4.36	0.683	4	Accepted
Exposure to vibration when executing tasks on site.	4.36	0.487	5	Accepted
Exposure to cold and heat stress on site.	4.28	0.741	6	Accepted
Exposure to noise on site.	4.20	0.624	7	Accepted
Exposure to humidity on site.	4.03	1.028	8	Accepted

To measure the reliability of the statistical dataset, the Cronbach’s Alpha coefficient was used as shown in Table 4.22. Based on 8 standardized items, the Cronbach’s Alpha coefficient was 0.87. The results indicate that the Cronbach’s Alpha internal consistency is good and reliable since it surpasses the acceptable value of 0.7 and is within the standardized zero to one scale.

Table 4.22: Reliability of statistical data

Reliability Statistics		
Cronbach's Alpha	Cronbach's Alpha Based on Standardized Items	N of Items
0.843	**0.866**	8

4.6. Chapter Summary

This chapter presented two sets of research data pursuant to the mixed methods including qualitative and quantitative data. The qualitative data was collected from three case projects in Free State province of South Africa and statistical data obtained from 116 construction personnel working in the construction industry within Free State including construction personnel registered with professional counsils, construction managers, quantity surveyors, site agents, forepersons, supervisors, artisans, plant operators, and general workers. Both the qualitative and quantitative data were presented to respond to the research objectives.

CHAPTER 5: CROSS-CASE DATA ANALYSIS

5.1. Introduction

This chapter presented a synopsis of qualitative findings reported in Chapter 4 through case studies 1, 2, and 3. A cross-case analysis method was adopted to compare qualitative data obtained from three case studies. The research data were then presented in this section using themes adapted from research objectives, hence, thematic analysis. The research analysis chapter endeavoured to address the five research objectives, namely:

- Identify the best practices of using wearable technology to leverage data metrics to investigate fatigue risk factors.
- Describe how to use wearable technology to evolve early fatigue related interventions to help construction personnel.
- Evaluate how wearable technology would inform about fatigue risks for the work environment and methods of work.
- Evaluate how wearable technology would inform about fatigue risks for plant and equipment operation.
- Develop a wearable technology protocol that would help reduce fatigue risk factors on construction sites.

5.2. Perceived best practices for using wearable technology to investigate fatigue

This section responded to the first research question which asked, what are the best practices for using wearable technology to leverage data metrics to investigate fatigue related risk areas? The research question sought to uncover construction personnel's perceived effectiveness of WT to monitor fatigue risk factors. The WT effectiveness according to construction personnel were presented in Chapter 4, Case Projects 1 to 3. Semi-structured interviewes were conducted across all three case projects; Refer to Tables 3.3. The researcher discovered that construction personnel had extensive experience conducting construction activities. To determine the best practices of using WT to investigate fatigue risks, construction personnel were asked several questions as indicated in Tables 4.2, 4.7, and 4.12. These questions encompassed 'construction personnel's understanding of WT, understanding of what is meant by fatigue, perceived best practices of WT, the need for WT on construction sites, as well as perceived effectiveness of WT during construction tasks undertaking.'

Table 5.1 presents a cross-case analysis of three case projects from which the qualitative data were collected using semi-structured interviews to address the first research objective. The construction personnel in case project 1 described WT best practices for fatigue risks reduction as its ability to effectively monitor physiological signals such as heart rate, blood pressure, pulse, etc based on their experience of using smartwatches at the gym and some on a regular basis. The construction team in case project 1 further stated that timely communication of fatigue data to management and construction personnel is one of the best practices of WT.

> The supervisor in case project 1 alluded saying, *"the best practice of WT is its capability to improve health and safety reporting as well as time management during construction undertaking"*.

In case project 2, construction personnel mentioned that WT best practices include proactive detection of internal or latent sicknesses.

> *"Some of us have high blood pressure, therefore WT's best practices would include blood pressure, heart rate, movement, and heat or cold rate monitoring when we are working on site"*, said the diesel truck operator in case project 2.

In case project 3, the construction team highlighted that WT's abilities to regulate construction personnel's exhaustion and fatigue levels on site is one of its many best practices.

> *"Another best practice of WT is that it helps improve construction workers' alertness and reduce fatigue by notifying workers to take regular rest breaks when performing construction tasks on site",* emphasized the driver in case project 3.

> The TLB operator in case project 1 also said, *"The best practice of WT is that it can notify workers to rest, thus, enhancing productivity since workers will always be on their best energy to work after taking rest breaks."*

Table 5.1: Best practices of wearable technology (*Cross-Case 1 to 3)*

Elements (Questions)	**Responses**			**Remarks**
	Case 1	**Case 2**	**Case 3**	
What are the best practices for using wearable technology to leverage data metrics to investigate fatigue related risk areas?	Yes	Yes	Yes	The best wearable technology practices for fatigue reduction are its ability to: • Monitor physiological signals (heart rate, blood pressure, etc.) • Proactively detect Internal sickness. • Communicate fatigue data to managers and workers timeously. • Regulate construction personnel' exhaustion and fatigue levels on site. • Improve time management. • Improve health and safety reporting. • Notify construction personnel to take regular rest breaks.

(**Source:** The researcher)

5.3. Wearable technology to evolve early fatigue interventions

This section responded to the second research question which asked, how can wearable technology be used to evolve early fatigue related interventions to help construction personnel? The researcher examined the construction personnel's understanding of how WT could be used on construction job sites and during construction activities to monitor fatigue risks for construction personnel. To achieve this objective, semi-structured interviews were conducted across case projects 1, 2, and 3 as described in Chapter 4. This objective was explored using three subheadings including, 'the benefits of using WT to monitor fatigue, WT's limitations during project undertakings, and effectiveness of WT to monitor fatigue risks factors.'

Table 5.2 presents a cross-case analysis of three case projects from which qualitative data through semi-structured interviews were collected to achieve the second research objective. When asked about how would WT evolve early fatigue interventions to help construction personnel? The construction manager and quantity surveyor in case project 2 highlighted that WT would raise awareness about workers' physical and mental health and wellbeing to identify fatigue risks and evolve early fatigue interventions. In case project 1, the plumber, tiler, 2 TLB operators, Bobcat operator, tipper truck operator, and 3 bricklayers expanded by stating that WT could be used on site to monitor how much energy a worker uses to prevent overexertion. Furthermore, the construction workers in case project 1 mentioned that WT could be used to alert workers to hydrate when needed on site. More telling is the statement made by the foreperson, supervisor, and director in case project 3, indicating that WT could evolve early fatigue risk interventions by proactively detecting latent health factors that might be detrimental to workers wellbeing.

> The carpenter in case project 1 elaborated, saying, *"Wearable technology would allow employers to communicate workers' fatigue levels with construction personnel to ensure sufficient rest times and improved health, safety, and production"*.

The supervisor, driver, and foreperson in case project 3 alluded that WT could monitor brain activity, visual cues, and microsleeps in real-time to dodge fatigue's negative effects. The construction personnel in case project 3 underscored that WT would flag workers' early warning signs such as sleeplessness and stress to avoid injuries and fatigue during construction activities. The smooth drum roller and TLB operators in case project 2 also cited that WT could be used to monitor vital signs such as overexertion, exhaustion, blood pressure, etc. and address such signals before causing fatigue risks.

Table 5.2: Wearable technology for early fatigue risks detection (*Cross-Case 1 to 3)*

Elements (Questions)	Responses			Remarks
	Case 1	Case 2	Case 3	
How can wearable technology be used to evolve early fatigue related interventions to help construction personnel?	Yes	Yes	Yes	Wearable technology could be used to: • Inform a safe work environment for construction personnel. • Monitor construction personnel's energy levels to prevent overexertion. • Alert construction personnel to hydrate when needed on site. • Allow communication regarding fatigue between the employer and construction personnel. • Raise awareness about construction personnel's physical and mental wellbeing. • monitor brain activity relative to fatigue, visual cues, and microsleeps. • Give construction personnel early fatigue warning signs to avoid injuries and fatigue.

(**Source:** The researcher)

5.4. Wearable technology to inform about fatigue risks for the work environment and methods

This section responded to the third research question which asked, how would wearable technology inform about fatigue risks for the work environment?. In response to the research question, the researcher interviewed construction personnel across case projects 1, 2, and 3 to investigate how the use of WT would help inform about fatigue risks in the workplace including methods of work used by construction personnel on site. To retort to this research question, several elements were explored including 'the experience of workers when working for elongated period on site, work environment, project tasks requirement, difficulties of working around the construction site, material handling, work methods used by construction personnel, as well as the effects of work environment and methods contributing to fatigue.'

Table 5.3 presents a cross-case analysis of three case projects from which qualitative data through semi-structured interviews were collected to address the third research objective. When the researcher enquired about construction personnel's understanding and perceived usefulness of WT to help inform about fatigue risks for the work environment and methods, the construction workers in case project 1 suggested that WT would help notify them to take rest breaks or to continue working.

> *"With the help of WT, workers would be encouraged to take responsibility for their personal well-being and time management while in the workplace conducting construction tasks",* reiterated the supervisor in case project 1.

The forepersons, quantity surveyor, and estate manager in case project 1 emphasised that regulating construction personnel's schedule relative to their exhaustion rate would inform about fatigue risks for the work environment and methods.

The construction personnel in case project 1 also highlighted that WT would inform about fatigue risks by proactively determining health and fatigue risks sources during project undertakings. The construction manager, quantity surveyor, and steel fixing specialist in case project 2 suggested that sensors could be installed around the areas where workers often conduct their daily tasks to monitor their energy and exhaustion levels, allowing them to better take care of themselves. The broomer and smooth drum roller operators in case project 2 mentioned that WT would help identify and inform the employer to upgrade some of the processes that cause fatigue in the workplace to ensure construction workers' HSW.

> *"Wearable technology would inform about fatigue risks by detecting the levels of vibration and comfortability emanating from the workplace and work methods. This would allow the employer to improve the work environment and methods before they cause fatigue or musculoskeletal disorders"*, retorted the brush cutter operator in case project 3.

Table 5.3: Wearable technology to inform about fatigue risks for the work environment and methods (*Cross-Case 1 to 3)*

Elements (Questions)	**Responses**			**Remarks**
	Case 1	**Case 2**	**Case 3**	
How would wearable technology inform redesigning the work environment and methods of work to reduce fatigue related risk factors?	Yes	Yes	Yes	Wearable technology would inform redesigning work environment and methods by: • Notifying construction personnel to take rest breaks or continue working. • Encouraging construction personnel to take responsibility of their well-being and that of others. • Regulating construction personnel's schedule relative to their exhaustion rate. • Determining the source of fatigue risks during project undertakings. • Enabling workers to monitor exhaustion levels to better take care of themselves. • Upgrading work processes in the workplace. • Tracking movement and concentration levels. • Detecting vibration levels emanating from the plant to allow the employer to fix the machines to avoid fatigue & musculoskeletal disorders.

(**Source:** The researcher)

5.5. Wearable technology to inform about fatigue risks for plant and equipment

This section responded to the fourth research question which asked, how would wearable technology inform about fatigue risks for construction plant and equipment? The qualitative data were thematically presented in chapter 4. The researcher interviewed construction personnel including artisans, plant operators, construction managers, forepersons, supervisors, and persons registered with professional counsils such as SACPCMP, ECSA, SACQSP, SACAP, etc. across case projects 1, 2, and 3 to address the fourth research objective. Factors including 'types of plant and equipment, risk factors associated with plant and equipment, and WT to inform about fatigue risks for plant and equipment' were interrogated to retort this research question.

Table 5.4 presents a cross-case analysis of the three case projects from which qualitative data through semi-structured interviews were collected to accomplish the fourth research objective. When asked about how would WT inform about fatigue risks for plant and equipment, the construction workers in case project 1 said that installing WT powered with sensors that would monitor plant operators' air quality, temperature, etc. would help inform about fatigue risks. The grader operator and shutting specialist in case project 2 also mentioned that WT would help in detecting early fatigue risk factors affecting plant operators on site.

> *"It would also detect various latent elements, depending on the work conducted on site to ensure plant operators' HSW",* reiterated the grader operator in case project 2.

> *"The technology imbedded in plant or equipment would improve productivity since plant operators would be aware of fatigue risk factors, thus, working efficiently and using safe work procedures"*, reiterated one of the brush cutter operators in case project 3.

The drum roller operator in case project 3 remarked that WT would inform about fatigue risks for plant and equipment by adding devices to plant or operators to detect risky exertion to reduce risky manual handling, bending, and twisting.

> *"Wearable technology would also inform about fatigue risks by incorporating sensors that can notify operators when working in awkward postures"*, stressed the brush cutter operator in case project 3.

> *"Technological advancements in plant and equipment would automatically adjust safety belts by sensing the size of the operator. The sensors would further detect the machine's comfortability, air quality, noise levels, and vibration levels to inform the operator to wear specific PPE. This will minimise health risks and fatigue",* explained the drum roller operator in case project 3.

Table 5.4: Wearable technology to inform about fatigue risks for plant and equipment (*Cross-Case 1 to 3)*

Elements (Questions)	**Responses**			**Remarks**
	Case 1	**Case 2**	**Case 3**	
How would wearable technology inform redesigning plant and equipment to reduce fatigue related risk factors?	Yes	Yes	Yes	Wearable technology would inform redesigning plant and equipment by: • Installing sensors in machines to monitor operators, air quality, and temperature. • Improving the process of operating construction plant will ensure the wellbeing of operators. • Detecting operators' internal health issues to avoid collapse during work. • Proactively monitoring indicators including heart rates, and blood pressure to ensure that plant operators remain healthy and safe on site. • Increasing efficiency on site to protect plant operators from injury or fatality. • Incorporating devices to detect risky exertion, manual handling, bending, and twisting.

(**Source:** The researcher)

5.6. Wearable technology protocol for fatigue risks reduction

This section responded to the fifth research question which asks, how will the development of a wearable technology protocol help reduce fatigue risk factors on construction sites? The study aimed to develop a WT protocol that would help reduce fatigue risk factors on construction sites. The four preceding objectives of this research explored various aspects that assisted in developing a WT protocol to reduce fatigue risks for construction personnel. The themes that emerged from the findings of this study include the perceived best practices of wearable technology by construction personnel, perceived effectiveness of wearable technology to monitor construction personnel's fatigue risks in South African context, wearable technology to inform about fatigue risks for the work environment, methods of work, as well as plant and equipment. The researcher determined that construction personnel across the three case projects had extensive experience working in the construction industry. Moreover, they had experience of using WT since the majority of workers used smartwatches for fitness purposes and fashion accessory. Therefore, to initiate actions towards developing a WT protocol, the researcher integrated the research objectives into a cluster of insights that would help reduce fatigue risk factors.

The findings of this study composed subjective fatigue data akin to the four above-mentioned research objectives. The WT protocol was therefore developed using subjective results of the mixed methods including qualitative and quantitative data. The qualitative data was collected using open-ended semi-structured interviews which was then analysed through the cross-case and thematic analysis methods. The quantitative data were obtained through survey questionnaires and analysed descriptively using the IBM SPSS Statistics version 29.0.1.1 to derive the mean scores and standard deviation for each research variable or construct relating to fatigue and WT. The researcher then developed a wearable technology protocol as demonstrated in Figure 5.1. The following five steps describe the procedure to be followed when implementing the WT protocol to reduce fatigue risk factors on construction sites.

Step 1: Select WT suitable for monitoring fatigue

The first step of the protocol involves the selection of relevant WT to monitor construction personnel's fatigue while undertaking construction activities on site. This step was influenced by the first research objective which sought to identify the best practices of using wearable technology to leverage data metrics to investigate fatigue related risk areas. The qualitative results across all three case projects highlighted that WT could monitor various indicators including physiological signals such as heart rate, blood pressure, temperature, etc. The construction personnel in case project 2 mentioned that WT equipped with sensors that could monitor blood pressure, heart rate, movement, and heat or cold stress would be effective in sleuthing fatigue risks. Hence, the knowledge of what each WT measures is paramount and would allow construction personnel to select suitable WT for fatigue monitoring on site.

The quantitative data highlighted various indicators that would help construction personnel to decide on the selection of suitable WT to monitor fatigue risks. The MSs of all the variables were above the midpoint of 0.25, with the Cronbach's Alpha internal consistency that surpass the acceptable value of 0.70. The literature reviewed in this study highlighted that construction personnel work in a complex, uncertain, and extremely dangerous environment perpetrating countless psychosocial harm, musculoskeletal disorders, ergonomic hazards, etc. Therefore, the selection of suitable WT is necessary to avoid damage to ligaments, muscles, and cognitive strength of construction personnel.

The literature suggested that some of the wearable technology that should be selected for fatigue risks monitoring in construction work environment include:

- Smart clothing equipped with sensors that would monitor posture, movement, and exertion levels, thus providing real-time feedback to prevent overexertion and possible fatigue risks.
- Smart helmets and EEG headbands equipped with sensors that would monitor environmental conditions such as temperature, humidity, etc.; brain activity, heart rate variability, worker cognitive fatigue levels, and eye movement during construction activities.
- Wearable exoskeletons that would assist workers to lift heavy objects and perform repetitive tasks by redistributing weight and reducing strain on muscles, thus reducing chances of physical fatigue risks.
- Environmental sensors to monitor air quality, noise levels, and other factors to reduce fatigue risk factors.
- Augmented reality (AR) with features that would provide real-time instructions as well as health and safety alerts.
- Biometric monitoring devices equipped with sensors that would monitor heart rate, hydration levels, and stress indicators to identify signs of early fatigue risks.

Step 2: Deploy WT to monitor fatigue risks in real-time

The second step of the protocol involves the adoption of WT to monitor physical and mental fatigue risks on site. This step was influenced by the second research objective which intended to describe how the use of WT would evolve early fatigue interventions to help construction personnel. The construction personnel in case project 2 believed that WT would make construction personnel to be aware of their exposure to physical and mental fatigue risks on site. In case project 1, the workers were convinced that WT could be used on site to monitor workers' energy expenditure levels to prevent overexertion. The construction personnel in case project 1 also mentioned that WT could be used to alert workers to hydrate when needed on site. Moreover, the forepersons, supervisor, and director in case project 3 indicated that WT could be used to proactively detect latent health factors that might be detrimental to workers wellbeing. AL-Sahar et al. (2021) affirms the effectiveness of using WT for sleuthing hidden health effects that transpire because of construction activities or biologically. Therefore, the following procedure should be followed to monitor fatigue risks in real-time:

- A thorough assessment of the construction site should be conducted to identify fatigue-inducing factors.
- A baseline threshold for fatigue risks monitoring should be established before the deployment of WT on site.
- An AI-driven algorithms should be developed to monitor deviations from the baseline fatigue levels.

- A suitable WT should be selected based on the assessment conducted and integrated to the existing health and safety procedure or equipment for fatigue risk monitoring during work shifts.
- EEG patterns, brainwave activity, heart rate variability, and eye movements should be tracked during work shifts.
- The AI-driven algorithms imbedded in WT should automatically alert construction workers of any fatigue risks in real-time using Bluetooth or Wi-Fi for data transmission.

Step 3: Establish a centralised database system to analyse and communicate objective fatigue data

The third step includes establishing a synchronized database system to analyse and communicate fatigue data. This step was influenced by the first, second, third, and fourth research objectives. The first and second research objectives intended to identify the best practices of using WT to leverage data metrics to investigate fatigue risks and describe how to use WT to evolve early fatigue interventions to help construction personnel. The third and fourth research objectives aimed to evaluate how WT would inform about fatigue risks for the work environment, work methods, as well as plant and equipment. The interviewees believed that a centralised database system is required to analyse, interpret, and communicate fatigue data pursuant to the work environment, work methods, as well as plant and equipment.

The broomer and smooth drum roller operators in case project 2 mentioned that WT would help inform the employer to upgrade some of the processes that cause fatigue in the workplace to improve workers' HSW. The construction team in case project 1 stated that timely communication of fatigue data to management and construction personnel is one of the best practices of wearable technology. Moreover, the carpenter in case project 1 elaborated, saying, *"WT would allow employers to communicate workers' fatigue levels with construction workers to ensure sufficient rest times and improved health, safety, and production"*. This remark is consistent with Haghighi et al. (2020) that WT such as flexible band equipped with EEG sensors, brainwave technology detectors, Bluetooth communication would communicate fatigue results and alert workers about possible microsleeps on site and support their physical and mental wellness. Wang et al. (2023) conducted a technical feasibility study using a wireless electroencephalography (EEG) device for real-time mental fatigue monitoring. The results suggested that a wireless EEG system paired with deep learning could detect mental fatigue in real-time with an accuracy of 88.85% (Wang et al., 2023). Therefore, establishing instruments for communicating fatigue results in real-time is paramount to reduce workers' fatigue in construction endeavours.

As a result, this protocol would incorporate a synchronized system which would be projected using devices including cellphones and computers to display workers' fatigue data in real-time for ease of fatigue data monitoring and communication. The real-time fatigue data communication would be achieved through the adoption of the internet of things (IoT) supported by Bluetooth and WiFi for fatigue data transmission, aggregation, and analysis. The centralised database should followed this procedure to monitor and communicate fatigue data in real-time:

- Wearables equipped with Bluetooth should be deployed to monitor and transmit early fatigue signs.
- Workers should be trained on how to read fatigue data in real-time through their devices and/or centralised database.
- The centralised database should be equipped with Bluetooth and Wi-Fi for real-time fatigue data aggregation and analysis.
- Fatigue data should be collected and stored in a secured and encrypted cloud database for long-term fatigue trend analysis.
- Long-term fatigue data should be reviewed regularly and communicated to workers and supervisors to improve fatigue interventions, health and safety culture, and centralised database programme for timely communication. This would ultimately help improve construction workers' health, safety, and productivity through data-driven fatigue management strategies.

Step 4: Establish subjective fatigue intervention strategies

The fourth step involves the establishment of practical fatigue intervention startegies to aid WT deployment and minimise fatigue risks on construction undertakings. This step was influenced by the second research objective which aimed to describe how the use of WT would evolve early fatigue interventions to help construction personnel. Gurubhagavatula et al. (2021) suggests that workplace fatigue poses a need for appropriate intervention strategies to reduce fatigue risks including determining shifts duration, addressing operational needs, recognising factors that contribute to fatigue risks, understanding evidence-based countermeasures for fatigue interventions, and selecting workplace-specific strategies for managing work hours. Therefore, the following fatigue intervention strategies would apply to the South African (SA) construction context to foster a healthy and safe work environment in addition to WT deployment:

- Implement an adaptive work rest scheduling strategy that allows workers to take rest breaks based on detected fatigue levels.
- Develop risk alert mechanisms including haptic feedback or auditory warnings to alert workers when their fatigue risks reach critical levels.
- Adjust the work environment based on real-time fatigue data communication for timely fatigue interventions including reduced noise and vibration levels, minimised exposure to heat or cold, etc.

Step 5: Considerations for compliance and usability of fatigue data on construction sites

The fifth step highlights the need to comply with privacy law and fosters ethical handling and usage of fatigue data obtained using WT. Anwer, et al. (2021) reported that technical issues and practical concerns such as signal artifacts, limited validity, undefined fatigue thresholds, as well as user acceptance and privacy are important aspects that necessitates compliance and consideration to avoid impediment to WT adoption and usability on SA construction sites. Therefore, the following procedures should be considered for compliance and usability of fatigue data on construction sites:

- Privacy and ethical considerations: ensure compliance with data protection laws and ethical guidelines.
- WT adoption on construction sites should consider ergonomic design to minimise interferance with work performance.

Step 6: Reduce risks associated with fatigue on construction sites

The final step reflects the outcome of positive response to communicated fatigue results for healthy and safe measures, which would lead to reduced fatigue risks in the work environment. This step stems from the second research objective which sought to describe how the use of WT would evolve early fatigue interventions to help construction personnel. The literature reviewed in this study revealed that construction personnel experience various kinds of fatigue risks including exposure to physically demanding activities leading to musculoskeletal impairments and reduced cognitive performance and strength (Collins, 2019). Construction personnel also work in environments that expose them to heat, vibration, humidity, confined spaces, irregular topographies, cold stress, and long work shifts (Al-Bouwarthan et al., 2019; Caldwell et al., 2019). These exposures have been reported to increase construction personnel's physical and mental fatigue risks (Bangaru, et al., 2022; Goodson, 2023). The construction personnel in this study also stated that they often experience all these fatigue risks; emphasising the need for WT to monitor fatigue risk factors on site.

Nonetheless, the interviewees and RPs in this study believed that using WT would lead to reduced fatigue risks. For instance, the construction personnel in case project 3 suggested that WT would help monitor brain activity, heart rate variability, visual cues, movement, and microsleeps in real-time to dodge fatigue's negative effects. The workers in case project 3 underscored that WT would give workers early fatigue warning signs to avoid injuries during construction activities. Anwer et al. (2021) supported the notion with their recent study on 'physiological metrics as a real-time measurement of fatigue in construction workers'. They reviewed 23 studies from nine countries and concluded that factors such as heart rate, heart rate variability, electromyography, skin temperature, motion-based jerk, and ratings of perceived exertion are good indicators of fatigue risks (Anwer et al., 2021). Therefore, prioritising excellent selection of relevant WT, WT utility, fatigue monitoring and analysis, communication, implementation of fatigue intervention strategies, and consideration for compliance and usability of fatigue results would ultimately lead to reduced fatigue risk factors in construction endeavours as indicated in Figure 5.1.

Figure 5.1 below presents a wearable technology protocol for fatigue risks reduction in construction. This six-step protocol outlines a procedure to be followed by construction personnel to monitor physical and cognitive fatigue risks on sites. The protocol was developed from the qualitative and quantitative results of this study in alignment with the literature reviewed. The system of rules and procedure to be followed when monitoring fatigue include:

1. The selection of suitable WT to monitor fatigue risks.
2. The Deployment of appropriate WT to monitor fatigue risks in real-time.
3. The establishment of a centralised database system to analyse and communicate objective fatigue data.
4. The establishment of subjective fatigue intervention strategies.
5. Considerations for compliance and usability of fatigue data on construction sites.
6. The reduction of risks associated with fatigue on construction sites.

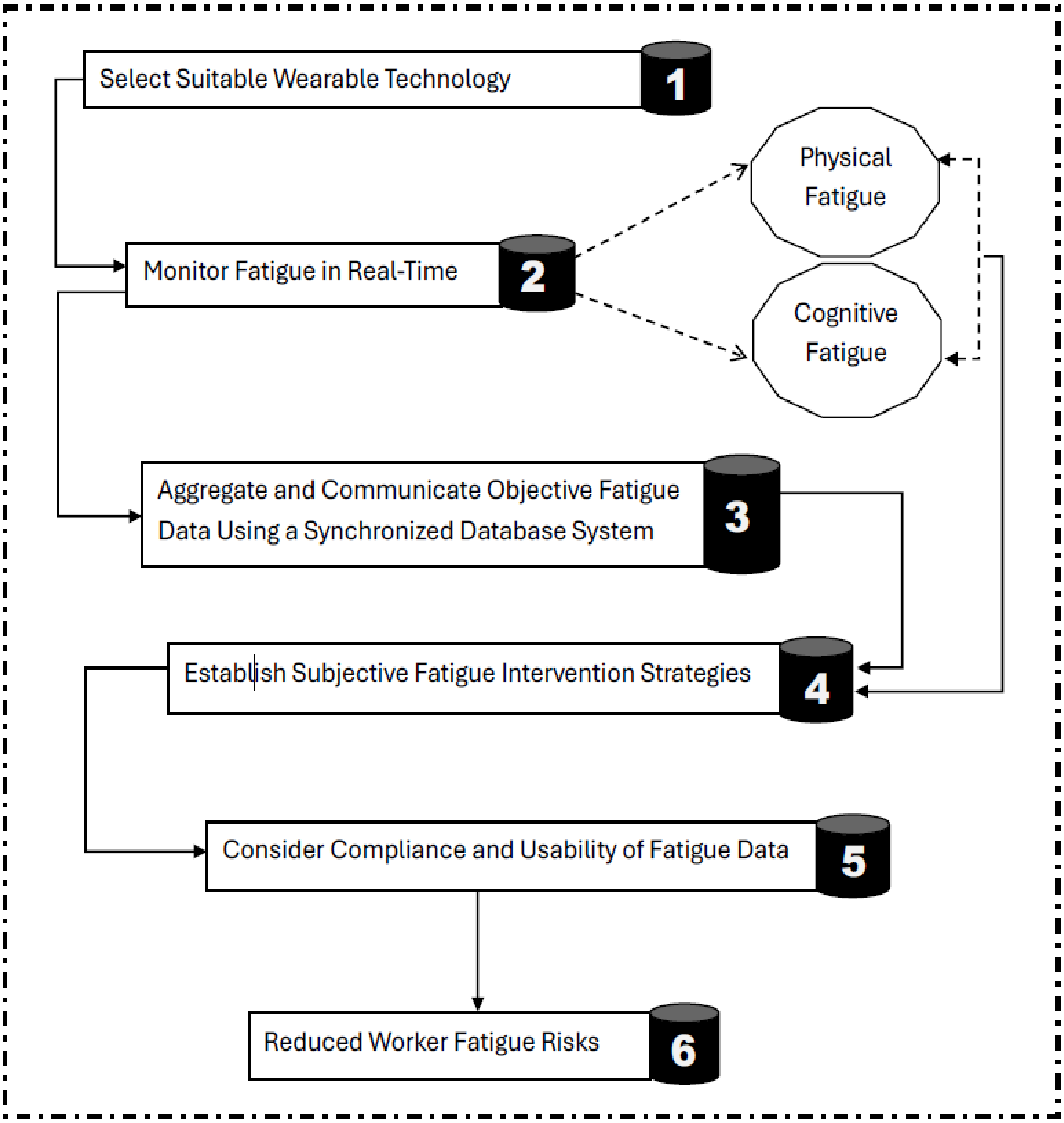

Figure 5.1: Wearable technology protocol for fatigue risks reduction

5.6.1. Application of a wearable technology protocol on construction sites

The wearable technology protocol should be adapted on construction sites by following the six-step procedure for fatigue risks reduction as outlined in Figure 5.1. The application of the protocol should begin with the selection of suitable WT for all construction personnel involved in project undertakings on site. Secondly, the selected wearable technology would be deployed on site to monitor construction personnel physical and mental fatigue while they are conducting construction activities. The fatigue data would be aggregated, analysed, and communicated to all stakeholders concerned through a centralized database system such as a computer or cellphone equipped with Bluetooth or WiFi. Thereafter, the subjective fatigue intervention strategies would apply to strengthen the objective fatigue data obtained using WT. Lastly, compliance with privacy laws such as the

Protection of Personal Information Act (POPIA) would be considered to ensure that construction personnel's privacy and processing their personal information is protected. This would ultimately reduce fatigue risk factors in construction work environment, work methods, and plant and equipment operation.

5.7. Chapter Summary

This research successfully analysed the qualitative data derived from three case studies which were presented in Chapter 4. The qualitative data was analysed using cross-case and thematic analysis methods. The research themes were extracted from the five research objectives. The research intended to identify the best practices of wearable technology for fatigue monitoring, describe how the use wearable technology would evolve early fatigue interventions to help construction personnel, evaluate how wearable technology would inform about fatigue risks for the work environment, methods of work, as well as plant and equipment operation, and develop a wearable technology protocol that would reduce fatigue risk factors on construction sites. This chapter compared the three case studies to identify common themes, patterns, and variations across all three case projects situated in Free State province of South Africa. These results led to the development of a six-step wearable technology protocol that would subjectively and objectively reduce construction personnel's fatigue risks in the construction work environments. Then, the chapter concluded.

CHAPTER 6: CONCLUSION AND RECOMMENDATIONS

6.1. Introduction

This chapter presents a summary of the research findings, conclusion, and recommendations based on the objectives of this research. This section summarized the key findings of the study, recommended possible contributions to knowledge and pointed out implications to practice within the construction industry. Then, the chapter concluded.

6.2. Conclusions

This section summarises interview findings and survey questionnaire results. The results demonstrated alignment between the qualitative data and quantitative data. This indicated agreement and perceived need of WT to evolve fatigue interventions in construction project endeavours. The qualitative and quantitative results were promulgated and interpreted pursuant to research objectives of this study and reviewed literature.

This study aimed to develop a wearable technology protocol that would help reduce fatigue risk factors on construction sites. Thus, the objectives of the study included:

- Identify the best practices of using wearable technology to leverage data metrics to investigate fatigue risk factors.
- Describe how to use wearable technology to evolve early fatigue interventions to help construction personnel.
- Evaluate how wearable technology would inform about fatigue risks for the work environment and methods of work.
- Evaluate how wearable technology would inform about fatigue risks for plant and equipment operation.
- Develop a wearable technology protocol that would help reduce fatigue risk factors on construction sites.

6.2.1. Conclusions on best practices for using WT to investigate fatigue

This subdivision addressed the first research objective which endeavoured to identify the best practices of using wearable technology to leverage data metrics to investigate fatigue related risk areas. The results of this study indicated that the best practices of WT for fatigue risks reduction include inter alia real-time monitoring of physiological signals such as heart rate, blood pressure, etc. WT's ability to communicate fatigue data to construction managers and workers timeously, regulate construction workers' exhaustion and fatigue levels on site, improve time management, improve H&S reporting, and notify construction workers to take regular rest breaks are some of WT best practices.

The survey results established that assessing indicators such as heart rate, blood pressure, human pulse wave, body and skin temperature, human motion, human physiological signal, blood oxygen saturation level, power management, pressure imaging, respiration rate, brain activity rate, muscle activity rate, energy expenditure, oxygen saturation, workers' location, heat stress, fall, and heart rate variability could help monitor fatigue risks. These constructs were extracted from Table 2.4 and Figure 2.1, rated by 116 construction personnel working in the construction industry within Free State.

The quantitative results of the first research objective were a compilation of RPs grading eighteen (18) constructs which were extracted from the reviewed literature in Table 2.1. The MSs of all the eighteen WT best practices for fatigue monitoring were above the midpoint of 2.50, indicating that these indicators were accepted by RPs and deemed effective to monitor workers' fatigue on construction sites. The Cronbach's Alpha internal consistency was 0.90, demonstrating that the variables were excellent and reliable since the Cronbach's Alpha internal consistency surpassed the acceptable value of 0.7 while ranging within the standardized zero to one scale.

6.2.2. Conclusions on WT to evolve early fatigue interventions

This subdivision addressed the second research objective which aimed to describe how WT could be used to evolve early fatigue interventions to help construction personnel. The results of this study suggested that WT could be used to improve HSW of workers in the workplace by monitoring construction personnel's energy levels to prevent overexertion. This makes WT a needed resource for construction endeavours to evolve early workers' fatigue interventions and alert construction personnel to hydrate when needed on site and ensuring communication regarding fatigue between the employer and construction personnel.

The statistical results highlighted that construction workers are habitually exposed to fatigue risk factors akin to forceful exertion, static load, repetitive motion, bending, twisting movement, awkward posture, energy deficiency, reduced alertness, and material handling loads. These fatigue variables were extracted from Figure 2.3 and flagged by literature as key fatigue effects in construction. The RPs rated eight (8) variables and the MSs of all 8 risk factors were above the midpoint of 2.50. These risk factors had a Cronbach's Alpha internal consistency of 0.86 that surpassed the acceptable value of 0.7 and was within the standardized zero to one scale.

To evolve early fatigue interventions, the research also investigated the monitoring purposes of various wearable devices to reduce fatigue. The results show that WT such as smart belt, smart glasses, chest harness, etc. would help evolve fatigue interventions to protect construction personnel from fatigue harm. For instance, the belt device would detect high-risk of bending, twisting, and reaching; smart glasses would monitor construction personnel's fatigue. The chest harness would provide real-time measurement of vitals, location, health status, and construction personnel's H&S; patch would provide real-time reports of heat stress indicators and worksite heat assessment. The wrists monitor would assist in conducting hand-arm vibration (HAV) risk assessment, tool testing, exposure monitoring, and risk control appraisal; clip would enable fall alerts, self-alerts, and logging. Gloves would strengthen gripping and grasping action, adjust applied force, and balance between fingers; exoskeleton would distribute upper body weight, reduce fatigue, and muscle stress. Flexible band would help measure fatigue and alertness at real-time, eliminate microsleeps, and support construction personnel's wellness. These variables were extracted from Table 2.5, Table 2.6, and Table 2.7 of the literature review section.

The MSs of the 14 WT monitoring purposes were above the midpoint of 2.50, implying that construction workers support and accept these monitoring purposes as effective in sleuthing fatigue risk factors in construction. The results were sufficiently consistent and reliable with the Cronbach's Alpha internal consistency of 0.93. The reliability results surpassed the acceptable value of 0.7 and was within the standardized zero to one scale. The research findings also emphasised that raising awareness about construction personnel's physical and mental wellbeing is paramount to maintain their productivity levels and longevity. This is because the advent of fatigue might be caused by a combination of interrelated factors such as physical, mental, and environmental stressors. Therefore, proactive assessment of these factors would improve the HSW of construction personnel and give early fatigue warning signs to avoid injuries and fatigue.

6.2.3. Conclusion on WT to inform about fatigue risks for the work environment and methods

This subdivision addressed the third research objective which intended to evaluate how wearable technology would inform about fatigue risks for the work environment and methods of work. The findings of this study suggest that WT would help inform construction personnel and employers about fatigue risks in the work environment and methods of work used on site and encourage all stakeholders to take responsibility of their well-being and that of others. The results also show that there is a need to regulate construction personnel's work schedule relative to their exhaustion rate using WT to minimise the risk of fatigue or collapse on site due to overexertion. WT such as smart construction belt equipped with vibration alert response sensor, GPS, ABS belt buckle, and sensors that detect physiological signals would help collects data on location, activity, and environment, identify risky activities, and haptic response to inform construction personnel about fatigue risks.

The statistical results demonstrated that construction workers experienced fatigue in various forms. Sometimes fatigue emanated from tiredness/exhaustion, lack of sleep, irritation, work stress, work that requires concentration, headaches, and heat or cold stress. The MSs for six of the seven fatigue risk factors were above the midpoint of 2.50 and only one risk factor was below the 2.50 midpoint, evincing that construction workers were often exposed to fatigue risk factors including tiredness/exhaustion, sleepiness, irritation, work stress, reduced focus, headaches, and heat or cold stress. These variables were extracted from Table 2.2 and Table 2.3. The results were reliable with the Cronbach's Alpha internal consistency of 0.80 that was sufficiently good and surpassed the acceptable value of 0.7 while ranging within the standardized zero to one scale.

Therefore, to inform about fatigue risks for the work environment and methods necessitate determining the source of fatigue risks during project undertakings. This could be achieved by tracking construction personnel's movement and concentration levels to determine the sources of fatigue in the workplace. Also, detecting vibration levels emanating from construction machinery and equipment would allow the employer to repair the machines before they cause fatigue and musculoskeletal disorders. WT's ability to measure body vitals, biomechanical metrics, heat stress risks, and physical load monitoring would help detect early fatigue risks on site.

6.2.4. Conclusion on WT to inform about fatigue risks for plant and equipment operation

This subdivision addressed the fourth research objective which sought to evaluate how wearable technology would inform about fatigue risks for plant and equipment operation. The results of this study suggested that WT would inform about fatigue risks for plant and equipment operation by installing environmental sensors such as CO_2 sensors, volatile organic compound (VOC) sensor, temperature and humidity sensors, noise dosimeters, sound level meters, motion sensors, light sensors, and pressure sensors in machines to monitor air quality, humidity levels, light levels, air pressure, duration and level of noise over time, and temperature which plant operators are exposed to. WT equipped with environmental and biometric sensors would assist in improving plant operators' health and site safety. These sensors would help monitor heart rate, posture, air quality, body temperature, repetitive motions, and other fatigue risk factors that plant operators are exposed to. Thus, preventing injuries and improving construction workers and plant operators' HSW.

The statistical results indicated that plant operators are not involved with every machine on site, but they operate specific plant and equipment. For example, only a few plant operators were operating construction plant such as cranes, concrete trucks, forklifts, earthmovers, tipper trucks, and soil compactors. Most construction artisans used equipment such as hand drills, hand grinders, nail guns, and generators. The Cronbach's Alpha internal consistency of 0.63 indicated that the reliability of the results was questionable since it was below the acceptable value of 0.7. This lack of reliability could have been caused by plant and equipment operators not using every machine on site. Thus, rating other variables below the mid-point (e.g., > 2.50).

Although plant and equipment are not operated by every worker on site, plant and equipment still affect all construction personnel involved in construction undertaking. For instance, most construction workers and plant operators in this research experienced environmental loads including noise, vibration, cold and heat stress, etc. caused by plant and equipment during construction process. Hence, the RPs rated eight (8) variables which were extracted from the reviewed literature in Figure 2.1 and Table 2.3. The MSs of all the environmental loads were above the midpoint of 2.50, indicating that these loads affect many construction personnel not just plant operators. The

Cronbach's Alpha internal consistency was 0.87, indicating that the results are reliable and good since it surpassed the acceptable value of 0.7 while ranging within the standardized zero to one scale.

WT such as smart helmet equipped with sensors for noise, gas, temperature, heat stress, and blood pressure should be integrated to ensure situational awareness and location monitoring in real-time. This will help inform about fatigue risks for plant and equipment operation. Proactive monitoring of physiological signals including heart rates, and blood pressure would help ensure that plant operators remain healthy and safe on site. It would also protect plant operators from injuries or fatalities by incorporating devices that detect risky exertion, manual handling, bending, and twisting. Thus, allowing easy fatigue monitoring processes and increase efficiency on site.

6.2.5. Conclusion on WT protocol to reduce fatigue

To respond to the fifth research question which asked, how will the development of a wearable technology protocol reduce fatigue risk factors on construction sites? The study evaluated subjective indicators for fatigue investigation since WT was not administered on site. The researcher developed a WT protocol to reduce fatigue risks by integrating diplomatic and experimental protocols for a strategic synergistic procedure. This WT protocol would assist construction personnel to strategically administer WT for fatigue monitoring on site, help derive real-time fatigue data, allow construction personnel to aggregate and analyse fatigue data from a synchronized database, help communicate fatigue results, and help construction personnel to derive subjective fatigue interventions while considering compliance and usability of workers' fatigue data. This would then lead to reduced fatigue risks on site.

The results of this study revealed that construction personnel suffer numerous fatigue risk factors while conducting construction tasks on site. These findings are consistent with literature reviewed in the research. Notably, many construction stakeholders believed that WT would reduce workers' fatigue risks on site. The importance of the research results lies on the fact that the acceptance of WT by construction personnel means that WT could be administered and tested in South African construction sites.

6.3. Limitations of the Study

This study has potential limitations. The elements of the WT protocol are based on the findings from semi-structured interviews, survey questionnaires and literature reviewed. The research sample encompassed all construction personnel including professionals, managers, supervisors, forepersons, artisans, plant operators, general construction personnel, and cleaners. The expertise of these RPs influenced the results of this study and contributed to the development of a WT protocol for fatigue risks reduction. The limitations included:

- This research is exploratory in nature. Therefore, more research should be conducted to investigate fatigue in construction because this study did not provide the final or conclusive answers to the research questions, but merely explored the research topic in depth.
- The research sample composed of three construction projects within the Free State province of South Africa. This research sample does not represent all construction projects within South Africa. Therefore, conclusions on the results relating to fatigue intensity in construction could have been influenced by climate conditions of the central parts of South Africa.
- This research did not administer WT to RPs to test the best practices of using WT to reduce fatigue.
- Some of the construction personnel and plant operators did not know how to communicate in English. Therefore, some of the research information was translated from Sesotho, IsiZulu, Setswana, and IsiXhosa to English prior the presentation, analysis, and discussion of the results.
- There were time constraints in terms of research project completion. This study was undertaking within 22 months.
- The WT protocol was not tested or validated on a live construction project site.
- The exploratory nature of this research yielded unconclusive results, unvalidated protocol, and subjective data.

6.4. Implications for Practice

The findings of this study demonstrate how WT protocols may be utilised to reduce risks associated with fatigue on construction sites. However, it is not widely used in South African construction sites. Therefore, industry leaders, construction firms, and consulting firms should consider the following recommendations:

- Construction industry leaders should make provision within the regulations for monitoring workers' latent health issues including fatigue in construction endeavours.
- Construction stakeholders should incorporate fatigue monitoring procedures on site.
- Clients should incorporate the requirements for fatigue risks monitoring in the health and safety policy and specifications for all construction project endeavours.
- Consultants or professionals should plan for fatigue in the early stages of a project lifecycle.
- Contractors should conduct training and situation awareness about fatigue risks and effectiveness of WT in construction undertakings.
- Contractors should establish reporting mechanisms to allow workers to communicate their experiences of the work environment and possible fatigue factors.
- Construction personnel, plant operators, and managers should be mindful of fatigue while conducting construction tasks on site to avoid falls from height, collapse, reduced productivity, etc.

- Construction personnel should be encouraged to communicate or report fatigue risks they encounter or observe during construction undertakings on site.

6.5. Contributions to Future Research

Future research should further investigate the following:

- The adoption of WT for fatigue monitoring on construction sites.
- Analysis of fatigue indicators into epochs that can be used to decide whether a worker is fatigued or not.
- Testing the WT protocol to assess its effectiveness in sleuthing fatigue risks in construction.
- The results of this research were influenced by Free State construction personnel's perspective on fatigue and WT, which does not reflect a wider South African view. Future research should further examine construction personnel's fatigue from different cities and provinces of South Africa.
- Future studies should use the proposed WT protocol on construction sites to investigate fatigue-related risks.
- Inferential statistical analysis should be done to test the hypothesis of this research.
- The structural equation modelling should be conducted to represent the relationships between fatigue and WT variables identified in this research, and to test how well the hypothesized protocol can reproduce new covariances including theories.
- Future research should bridge the limitations of this exploratory study by validating the proposed WT protocol, investigating both subjective and objective fatigue results, and adopting a standardized data analysis methods to draw conclusions.

6.6. Concluding Remarks

The current study aimed to develop a wearable technology protocol that would help reduce fatigue risk factors on construction sites.

The key questions of this research were as follows:

- What are the best practices for using wearable technology to leverage data metrics to investigate fatigue risk factors?
- How can wearable technology be used to evolve early fatigue interventions to help construction personnel?
- How would wearable technology inform about fatigue risks for the work environment and methods of work?
- How would wearable technology inform about fatigue risks for plant and equipment operation?
- How will the development of a wearable technology protocol reduce fatigue risk factors on construction sites?

The findings of this study were all aligned to the acceptance of WT to reduce fatigue risks in construction. The 3 case studies highlighted that construction personnel suffer from fatigue risks daily with limited mechanisms for fatigue risks monitoring. The consensus from the cross-case analysis of the 3 case studies was that construction firms need a WT protocol that would help reduce workers' fatigue on site. The statistical data were collected from 116 construction personnel to investigate how would a WT protocol help to reduce fatigue risks on SA construction sites. The RPs perceived WT effective in sleuthing fatigue risks. Thus, showing optimism about a WT protocol that would help reduce fatigue risk factors that affect construction personnel on site.

This discovery allowed the researcher to develop a WT protocol that would help reduce workers' fatigue in construction. The WT protocol followed a six-step synergistic procedure to help select suitable WT, monitor fatigue risks, aggregate and analyse fatigue data, communicate fatigue results, consider compliance and usability of fatigue data to reduce construction workers' fatigue risks. The first step of the protocol involves the selection of suitable WT to detect fatigue while workers are conducting construction activities on site. The second step involves deploying WT for real-time monitoring of physical and mental fatigue risk factors. The third step includes the establishment of a synchronized database system to aggregate, analyse, and communicate objective fatigue data to allow ease of interpretation. The fourth step involves the establishment of subjective fatigue intervention strategies such as adaptive work rest scheduling strategy, fatigue risk alert mechanisms including haptic feedback or auditory warnings, and adjusting the work environment based on real-time fatigue data communication. The fifth step considers the importance of complying with privacy laws and protection of workers' fatigue data including POPIA. The final step reflects the outcome of positive response to communicated fatigue results for timely H&S interventions, resulting to reduced fatigue risks in the work environment.

This research uncovered that fatigue could be detected and monitored. The WT protocol developed in this study has the potential to reduce fatigue, bring fatigue risks awareness to construction personnel; protect the employers' financial resources which would have been spent on hospital bills; improve productivity; improve ethical consideration and compliance when using workers sensitive information, and reduce loss time due to mental distress and fatigue-induced accidents or injuries on site. However, due to limited research sample, lack of WT deployment on a construction project, and WT protocol not being tested; further research is required to validate the WT protocol by following the six-step synergistic procedure on different construction sites around South Africa.

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ANNEXTURES

ANNEXTURE A: INTERVIEW GUIDE

COVER LETTER

Attention: The respondents

Dear Sir/ Madam,

RE: DEVELOPING A WEARABLE TECHNOLOGY PROTOCOL FOR FATIGUE RISK REDUCTION ON CONSTRUCTION SITES

I would like to thank you for honouring my invitation and taking part in this research project. This research project aims to develop a wearable technology protocol for reducing fatigue risk on construction sites. The research study partially fulfils the requirement for the Master of Construction in Built Environment at the Central University of Technology, Free State (CUT).

To take this study forward, interviews with construction site personnel working on the construction project are required. The proposed interviews will comprise a short questionnaire and open-ended questions. The interview will be between 30 and 60 minutes. The interview will be conducted in person, and all communications will be recorded. Please note that the confidentiality of your responses to the interview will be protected.

Should you have any queries, please do not hesitate to contact Mr Sizolwakhe Mtetwa at smtetwa@cut.ac.za.

Yours sincerely,

Researcher	**Supervisor**	**Co-Supervisor**
Sizolwakhe Innocent Mtetwa	Lesiba George Mollo, PhD	Fidelis Abumere Emuze, PhD

SECTION A: GENERAL INFORMATION

(Mark by X in the relevant box)

1. Do you consent to this interview?

Yes	
No	

2. Please indicate your age.

20-29		30-39		40-49		50+	

3. Please indicate your gender.

Male		Female		Other	

4. Please name the project you work for.

-

-

5. Please indicate your Occupation/Position/Job description.

-

-

6. How long have you worked on this position?

-

-

7. Please specify the level at which you are working on site.

Ground Level	
Elevated Heights	
Both	

8. Please specify the type of project you are involved in.

Residential Building	
Commercial Building	
Industrial/Civil Works	
Institutional Building	

9. Please state your highest qualification.

-

-

10. Please state if you are registered with any council (i.e., SACONSTRUCTION PERSONNELCMP, ECSA, etc.)?

Yes	
No	

11. Please state your professional qualification(s).

-

-

SECTION B: THE INTERVIEW GUIDE

(Mark by X where necessary)

THEME 1: The identification of the best practices for using wearable technology to leverage data metrics to investigate fatigue-related risk areas.

1. What is your understanding of wearable technology?

2. Do you understand what is meant by fatigue?

3. What are some of the best practices of wearable technology known to you?

4. Please explain why do you think wearable technology is a needed resource on construction sites?

5. Do you think wearable technology would help you and your employer discover fatigue risk factors during the construction process on-site.

Yes	
No	
If no, please explain:	

6. Do you think wearable technology will allow you to execute construction tasks comfortably and without disturbance?

Yes	
No	
If no, please explain:	

THEME 2: The description of how to use wearable technology will evolve early fatigue-related interventions to help construction personnel.

1. What are the benefits of using wearable technology to reduce fatigue risk factors?

   -
   -
   -
   -
   -
   -

2. Do you think wearable technology can restrict you from doing your work properly?

Yes	
No	
If yes, please explain:	

3. How can wearable technology effectively reduce fatigue risk factors?

-
-
-
-
-
-
-

THEME 3: The evaluation of how wearable technology would inform redesigning the work method to reduce fatigue-related risk factors.

1. How do you feel when you are working for a long period on-site?

-
-
-
-
-

2. When undertaking tasks, are you usually exposed to the sun or work in a shaded area/indoor environment?

-
-
-
-

3. Does your work require you to perform tasks requiring bending, twisting, or repetitive work in awkward postures?

Yes	
No	
If yes, please explain:	

4. Do you have any difficulties when working around the site?

Yes	
No	
If yes, please explain:	

5. Do you experience exhaustion or dizziness when working on-site?

Yes	
No	

If yes, please explain:

6. How are the construction materials you work with delivered and handled on-site?

7. Does the work method you use on-site contribute to fatigue?

Yes	
No	

8. Please explain why you think the work method does or does not contribute to fatigue.

-

-

9. Please explain how you anticipate wearable technology would improve the work environment and work methods used on site.

-

-

-

-

-

-

-

THEME 4: The evaluation of how wearable technology would inform redesigning plants and equipment to reduce fatigue-related risk factors.

1. How do you understand the concept of “redesigning of plant and equipment”?

-

-

-

-

-

-

2. What type of plant or equipment do you operate on-site?

3. What risk factors are you usually exposed to when working with plant and/or equipment?

-

-

-

-

-

-

4. In your opinion, how can the use of wearable technology inform redesigning plants and equipment to reduce fatigue risk factors on-site?

-

-

-

-

-

-

—The End—

Thank you very much for taking the time to participate in the inter

ANNEXURE B: SURVEY QUESTIONNAIRE GUIDE

COVER LETTER

Attention: The respondents

Dear Sir/ Madam,

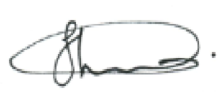
RE: DEVELOPING A WEARABLE TECHNOLOGY PROTOCOL FOR FATIGUE RISK REDUCTION ON CONSTRUCTION SITES

I would like to thank you for honouring my invitation and taking part in this research project. This research project aims to develop a wearable technology protocol for reducing fatigue risk on construction sites. The research study partially fulfils the requirement for the Master of Construction in Built Environment at the Central University of Technology, Free State (CUT).

This research aims to develop a wearable technology protocol that would help to reduce the risk of fatigue risk factors on construction sites. To take this study forward, survey questionnaires with construction professionals involved in projects are required. The survey questionnaires will comprise close-ended questions which will require approximately 10 – 15 minutes of participation.

Should you have any queries, please do not hesitate to contact Mr Sizolwakhe Mtetwa at smtetwa@cut.ac.za.

Yours sincerely,

Researcher	Supervisor	Co-Supervisor
		
Sizolwakhe Innocent Mtetwa	Lesiba George Mollo, PhD	Fidelis Abumere Emuze, PhD

SECTION A: GENERAL INFORMATION

(Mark by X in the relevant box)

12. Do you consent to this survey questionnaire?

Yes	
No	

13. Please indicate your age.

20-29		30-39		40-49		50+	

14. Please indicate your gender.

Male		Female		Other	

15. Please name the Company/Project you work for.

16. Please indicate your Occupation/Position/Job description.

17. How long have you worked on this position?

18. Please specify the level at which you are working on site.

Ground Level	
Elevated Heights	

Both	

19. Please specify the type of project you are involved in.

Residential Building	
Commercial Building	
Industrial/Civil Works	
Institutional Building	

20. Please state your highest qualification.

21. Please state if you are registered with any council (i.e., SACONSTRUCTION PERSONNELCMP, ECSA, etc.)?

Yes	
No	

22. Please state your professional qualification(s).

SECTION B: THE SURVEY QUESTIONNAIRE GUIDE

(Mark by X in the relevant box)

THEME 1: The identification of the best practices for using wearable technology to leverage data metrics to investigate fatigue-related risk areas.

1. Using a scale of 1 – 5 (1 being Poor and 5 being Excellent), please rate the reasons for using wearable technology to leverage data metrics to investigate fatigue risk factors. Please note the unsure (0) option. Scale 1 = Poor, 2= Fair, 3 = Good, 4 = Very Good, 5 = Excellent.

Reason	Poor……………………………….……………Excellent					
	0	**1**	**2**	**3**	**4**	**5**
Heart rate detection						
Blood pressure monitoring						
Human pulse wave monitoring						
Body and skin temperature monitoring						
Human motion detection						
Human physiological signal						
Blood oxygen saturation level						
Power management						
Pressure imaging						

Respiration rate monitoring						
Brain activity rate monitoring						
Muscle activity rate monitoring						
Energy expenditure detection						
Oxygen saturation						
Location monitoring						
Heat stress indication						
Fall alert monitoring						
Heart rate variability (HRV) monitoring						

2. Using a scale of 1 – 5 (1 being minor and 5 being major), please rate the extent to which you are exposed to the risk factors below. Please note the unsure (0) option. Scale: 1 = Minor, 2 = Near Minor, 3 = Neutral, 4 = Near Major, 5 = Major.

Risk Factors	Minor……….…………………………. Major					
	0	**1**	**2**	**3**	**4**	**5**
Mental and physical exhaustion						
Stressful work						
Repetitive work						
Sleep deprivation						
Blind spots						

Proximity within the work environment						
Intense ultraviolet rays cause heat stress						
Materials located far from the work site						
Confined work areas resulting in awkward postures						

THEME 2: To describe how to use wearable technology to evolve early fatigue-related interventions to help construction personnel.

1. Using a scale of 1 (Never) to 5 (Always), please rate the extent to which you experience the following types of fatigue on site. Please note the unsure (0) option. Scale: 1 = Never, 2 = Rarely, 3 = Sometimes, 4 = Very Often, 5 = Always.

Concepts	Never…………………………………………………………..Always					
	0	**1**	**2**	**3**	**4**	**5**
Physical fatigue						
Mental fatigue						

2. Using a scale of 1 – 5 (1 being Never and 5 being Always), please rate the frequency to which your work exposes you to the following risk factors while executing construction tasks on site. Please note the unsure (0) option. Scale: 1 = Never, 2 = Rarely, 3 = Sometimes, 4 = Very Often, 5 = Always.

Physical Load	Never…………………………..…………………………..….Always

	0	1	2	3	4	5
Forceful exertion						
Static load						
Repetitive motion						
Bending & twisting movement						
Awkward posture						
Energy deficiency						
Reduced alertness						
Material handling						

3. Using a scale of 1 – 5 (1 being minor and 5 being major), please explain the extent to which your work presents you with the following risk factors while executing construction tasks on site. Please note the unsure (0) option. Scale: 1 = Minor, 2 = Near Minor, 3 = Neutral, 4 = Near Major, 5 = Major.

Mental Load	Minor …………………………………………….………… Major					
	0	**1**	**2**	**3**	**4**	**5**
Irregular work hours						
Task demands						
Decision autonomy						
Job stress						
Co-worker relationship						

4. Using a scale of 1 – 5 (1 being Definitely Not and 5 being Definitely), please rate the wearable technology monitoring purposes to reduce fatigue risk factors on construction sites. Please note the unsure (0) option. Scale: 1 = Definitely Not, 2 = Probably Not, 3 = Possibly, 4 = Probably, 5 = Definitely.

WEARABLE TECHNOLOGY Monitoring Purposes	Definitely Not………………….……..…Definitely					
	0	**1**	**2**	**3**	**4**	**5**
Belt device to detect high-risk bending, twisting, and reaching						
Smart glasses to monitor the drivers and plant operators' fatigue.						
Chest device for mobile human monitoring; 24/7 health and safety observations in extreme environments						
Chest harness for real-time measurement of vitals; knowledge of location and health status; manage safety						

Patch for real-time reports of heat stress indicators; worksite heat assessment; training and consultation						
Belt for collecting data on location, activity, and environment; identification of risky activities; haptic response						
Wrists monitor for hand-arm vibration (HAV) risk assessment; tool testing; exposure monitoring; risk control appraisal						
Safety button for sending alerts and location data, press unique buttons for non-emergency or emergency response						
Clip for fall alerts; self-alerts, and logging						
Chest device to track body vitals, biomechanical metrics, and physical load monitoring						
Gloves to strengthen gripping and grasping action; adjust applied force and balance between fingers						
Exoskeleton to distribute upper body weight; reduce fatigue and muscle stress						

Flexible band to measure fatigue and alertness at real-time; eliminate microsleeps; support wellness						
Shoes to measure gait changes, impact, and fatigue						

THEME 3: To evaluate how wearable technology would inform redesigning the method of work to reduce fatigue-related risk factors.

1. Using a scale of 1 – 5 (1 being Very dissatisfied and 5 being Very satisfied), please rate your level of satisfaction with the working conditions on construction site(s) you are involved in. Please note the unsure (0) option. Scale: 1 = Very dissatisfied, 2 = Dissatisfied, 3 = Neither, 4 = Satisfied, 5 = Very satisfied.

Very dissatisfied……………………………..…………………………………..Very satisfied					
0	**1**	**2**	**3**	**4**	**5**

2. Using a scale of 1 – 5 (1 being never and 5 being always), please rate the frequency to which you experience the fatigue risk factors below while working on site. Please note the unsure (0) option. Scale: 1 = Never, 2 = Rarely, 3 = Sometimes, 4 = Very Often, 5 = Always.

Factors	Never……………………………………………….Always					
	0	**1**	**2**	**3**	**4**	**5**
Tiredness/Exhaustion						
Sleepy						
Irritation						

Work stress						
Reduced focus						
Headaches						
Heat or cold stress						

3. Using a scale of 1 - 5 (1 being Definitely Not and 5 being Definitely), please rate the extent to which you think the following wearable technology will inform redesigning work methods to reduce fatigue risk factors. Please note the unsure (0) option. Scale: 1 = Minor, 2 = Near Minor, 3 = Neutral, 4 = Near Major, 5 = Major.

Wearable Technology	Minor……………..……………….Major					
	0	**1**	**2**	**3**	**4**	**5**
Chest Device for heart rate, breathing, activity, posture, accelerometery, impact to track body vitals, biomechanical metrics, heat stress risks, and physical load monitoring during work task execution.						
Glove with pressure sensors in five fingers embedded processor, actuator, and battery to strengthen gripping and grasping action; adjust applied force and balance between fingers when working on site.						

Belt device for inertial measurement units, alert system to detect high-risk bending, twisting, and reaching.						
Exoskeleton for a mechanical support system, driven by pulleys to distribute upper body weight; reduce fatigue and muscle stress when undertaking tasks.						
Smart Boots with force and motion sensors, and control boards to measure gait changes, impact, and fatigue on site.						
Flexible band equipped with EEG sensors, brainwave technology detectors, and Bluetooth communication to measure fatigue and alertness in real-time; eliminate microsleeps; support on-site wellness.						

THEME 4: To evaluate how wearable technology would inform redesigning plant and equipment to reduce fatigue-related risk factors.

1. Using a scale of 1 (Never) – 5 (Always), please rate the extent to which you operate the construction plant or equipment below. Please note the unsure (0) option. Scale: 1 = Never, 2 = Rarely, 3 = Sometimes, 4 = Very Often, 5 = Always.

Plant & Equipment	Never…..…………………..…………….Always

	0	1	2	3	4	5
Excavator						
Crane						
Forklift						
Trucks						
Earthmoving plant						
Concrete plant						
Hand drill						
Hand grinder						
Nail gun						
Generator						
Soil compaction machine						
Others: ______________________________						

2. Using a scale of 1 – 5 (1 being Never and 5 being Always), please rate the frequency to which you experience the fatigue risk factors below while operating plant and equipment on site. Please note the unsure (0) option. Scale: 1 = Never, 2 = Rarely, 3 = Sometimes, 4 = Very Often, 5 = Always.

Environmental Load	Never…..…………..……………………Always					
	0	**1**	**2**	**3**	**4**	**5**
Noise						
Vibration						

Cold and heat stress						
Exhaustion due to the sun						
Humidity						
Awkward body movement						
Twisting and bending						
Repetitive Work						

3. Using a scale of 1 - 5 (1 being Definitely Not and 5 being Definitely), please rate the likelihood of wearable technology to inform redesigning plant and equipment to reduce fatigue-related risk factors. Please note the unsure (0) option. Scale: 1 = Definitely Not, 2 = Probably Not, 3 = Possibly, 4 = Probably, 5 = Definitely.

Definitely Not……………….……………………..……….………………………….Definitely					
0	**1**	**2**	**3**	**4**	**5**

—The End—

Thank you very much for taking the time to complete the survey questionnaire.

ANNEXTURE C: ETHICAL CLEARANCE

Central University of Technology, Free State

FACULTY OF ENGINEERING AND INFORMATION TECHNOLOGY

Department of Civil Engineering

APPLICATION FOR ETHICAL CLEARANCE TO CONDUCT RESEARCH IN THE FACULTY OF ENGINEERING, BUILT ENVIRONMENT AND INFORMATION TECHNOLOGY

The Central University of Technology (CUT) Research Ethics and Integrity Policy applies to all undergraduate and post graduate students, and staff members who conduct research on CUT campuses and outside the campus. CUT policy bounds any person who wishes to conduct research with CUT students and/or staff but is not CUT affiliated to abide by the ethics framework. All CUT members who conduct research take responsibility to implement this Policy.

1. APPLICANT INFORMATION

1.1.	**Title (Prof Dr /Mr /Mrs /Ms)**	Mr	
1.2	**Name(s) and Surname**	Sizolwakhe Innocent Mtetwa	
1.3	**Student / Staff number**	219005077	
1.4	**Department**	Built Environment	
1.5	**Campus**	Bloemfontein	
1.6	**Postal address**	137 Raymond Mhlaba Street Navalsig Bloemfontein 9301	
1.7	**Contact details**	Office	N/A
		Cell	0740863990
		e-mail	smtetwa@cut.ac.za
1.8	**Supervisor (s)/Project Leader**	Dr LG Mollo Prof. FA Emuze	
1.9	**Qualification registered for/Level of research**	***Please tick relevant option:***	
		Masters qualification	✓
		Doctorate	
		Independent research (Non-qualification purposes)	
1.10	**FRIC Approval Number (LS262a) (where applicable)**		
1.11	**Conflict of interest (Please underline/highlight):**		

	1) Personal relationship Yes/No 2) Financial benefit Yes/No
	If yes, please provide details:

2. DETAILS OF THE STUDY

2.1	**Approved/Proposed title of the study/project /dissertation/thesis**
Developing A Wearable Technology Protocol for Fatigue Risk Reduction on Construction Sites	
2.2	**Research question(s)**
The main research question of this study asks, "How can a wearable technology (WT) protocol assistin the reduction of fatigue risk factors on construction sites?" **The following sub-questions were formulated to respond to the above main research question.The sub-questions include:** • What are the best practices for using wearable technology to leverage data metrics toinvestigate fatigue-related risk areas? • How can wearable technology be used to evolve early fatigue-related interventions to help construction workers? • How would wearable technology inform redesigning the work method to reduce fatigue-relatedrisk factors? • How would wearable technology inform redesigning plants and equipment to reduce fatigue-related risk factors? • How will a wearable technology protocol reduce fatigue-related risk factors on construction sites?	
2.3	**Aim and objectives of the study**
This study aims to develop a wearable technology protocol that would help to reduce the risk offatigue risk factors on construction sites. Thus, the objectives of the study include: • Identify the best practices for using wearable technology to leverage data metrics to investigatefatigue-related risk areas. • Describe how to use wearable technology to evolve early fatigue-related interventions to help construction workers. • Evaluate how wearable technology would inform redesigning the work method to reducefatigue-related risk factors. • Evaluate how wearable technology would inform redesigning plants and equipment to reduce fatigue-related risk factors.	

- Develop a wearable technology protocol to reduce fatigue-related risk factors on construction sites.

2.4	**Research methodology**
2.4.1	**Research participants and their age brackets (where applicable, e.g. 10 Students from Civil Engineering Department)**

The research participants will encompass all site personnel, including professionals, managers, contractors, subcontractors, site agents, plant and equipment operators, foremen, artisans, and general workers from three case projects in Bloemfontein, South Africa.

2.4.2	**How will participants be selected/sampled?**

Purposive sampling will be used to choose a sample that will be useful to the objectives of thisresearch. The nature of this study necessitates the adoption of a heterogenous sample to engender various construction personnel that can contribute to the required research data.

2.4.3	**Research site(s) (e.g. Borong Construction Site)** **Please list**

Ruwacon Construction Site
Namcon Holdings Sites (x2)

2.4.4	**Data collection instruments (e.g. questionnaire(s)/interview schedule(s)/observation schedule(s)/artefacts/other)**

Semi-structured interviews
Questionnaires survey

2.4.5	**Data collection procedure (Please outline WHEN, WHERE and HOW data will becollected)**

QUALITATIVE DATA

When?

September 2023 – January 2024.

Where?

Three construction sites in Bloemfontein

- Residential development in Lilyvale
- Residential development in Woodlands
- Commercial building development in Mangaung

How?

By using semi-structured interviews.

QUANTITATIVE DATA

When?

January 2024 – April 2024.

Where?

	Bloemfontein (construction site projects) **How?** Using survey questionnaires.

3. PROPOSED PLAN OF STUDY/RESEARCH

	Set out your intended plan of work for the research, indicating important target dates necessary to meet your proposed deadlines	
	Research Tasks	**Proposed Deadlines**
	Data Collection	April 2024
	Interpretation of Data	June 202
	Discussion of Finding	June 2024
	Recommendations & Conclusion	July 2024
	Proofreading the Dissertation	July 2024
	Professional English Editing	August 2024
	Submission for Assessment	September 2024
	Publications for Master of Construction	
	Conference paper	March 2024
	Journal paper	July 2024

4. ETHICAL ISSUES AND RISK ASSESSMENT

In order to assess whether your proposed research is ethically compliant, ethics risks are categorised into four categories:

(1) Research involving minor risk
The likelihood of projected harm or inconvenience in the research is not greater than that experiencedin daily life.

(2) Research involving low risk
Research in which the only anticipatable risk is one of potential awkwardness or discomfort to theparticipants.

(3) Research involving medium risk
Research in which there is a possible risk of harm or discomfort, but where appropriate steps can betaken to lessen or moderate overall risk.

(4) Research involving high risk
Research in which there is a real and foreseeable risk of harm and discomfort, which may lead to aserious adverse event if not managed in a responsible manner.

4.1	**Will human research participants be used in yourstudy?** *Please mark with an X or √ in the Yes/No/N/A box*	✓ **Yes**	**No**	**N/A**

4.2	If yes, does the research study involve any of thefollowing:			
a) Children or youth under the age of 18 (Attach parental consent letter)			✓	
b) Individuals living with disabilities (physical, mental and/or sensory) (Attach consent letter of legal guardian)			✓	
c) Individuals that might find it difficult to make independent and informed decisions for socio, economic, cultural, political and/or medical reasons			✓	
d) Communities that might be considered vulnerable, thus finding it difficult to make independent and informed decisions for socio, economic, cultural, political and/or medical reasons			✓	
e) Individuals who might be vulnerable for age related reasons e.g. the elderly			✓	
f) Individuals whose spoken language differs from the languageused for the research (Make sure you translate your consent form and participant information sheet in the participants' first language – you shouldalso have an interpreter if you do interviews – describe it belowthe table)				
g) Women considered to be vulnerable (pregnancy, victimisation, marginalised etc.)			✓	
h) Other (Please explain):				

4.3	Will data collection involve any of the following:	Yes	No	N/A
	a) Access to confidential data without prior permission ofparticipants		✓	
	b) Participants expected to commit an act which might reduceself-respect or cause them to experience shame,embarrassment, or regret		✓	
	c) Expose participants to worrying or upsetting questions orto processes which may have disagreeable or harmful side effects		✓	

d) The use of stimuli, errands or procedures which may be experienced as stressful, harmful, or hostile		✓	
e) Any use of materials risky to human beings		✓	

4.4 If you answered "Yes", to any of the previously mentioned, explain (attach as an appendix) and justify. Explain, too, what steps you will take to minimise the potential stress/harm. *(Please indicate if it is not applicable to your study)*
N/A

4.5 Confidentiality of participants' identity				
4.5.1	**Will the identity and privacy of participants be protected through pseudonyms or other forms of identification and the use of an informed consent form, which specifies (in a language that participants will understand):** *Place an 'X or ✓' in the Yes/No box*	✓ **YES**	**NO**	**N/A**
4.5.2	**Please note that participants should be informed about the following (where applicable)**			
	a) The purpose/s of the research and how it is conducted	✓		
	b) The researcher, project leader and supervisor's identity, their institutional association and their contact details	✓		
	c) Voluntary participation of participants	✓		
	d) Making sure that participants' responses will be treated in a confidential manner	✓		
	e) Be transparent about any possible limits on confidentialitywhich may apply	✓		
	f) Ensuring participants that they are free to withdraw from the research at any time without any negative or undesirable consequences to themselves	✓		
	g) How the findings of the study will have any benefits, or mayreceive as a result of their participation in the research	✓		
4.5.2 Please attach the proposed consent and assent documents prepared to address all the above, if not a full explanation is needed explaining how will participants be respected and protected.				

5. DOCUMENTS TO BE ATTACHED TO THE APPLICATION

The following documents must be attached as a prerequisite for approval to undertake researchin the Department (where applicable)	
5.1	LS 262a approved by the FRIC (FEBIT)
5.2	Proof of registration/Funding received and funder reference details
5.3	Data collection instruments as identified under 2.4.4

6. DECLARATION BY THE APPLICANT

I undertake to use the information that I acquire through my research, in a balanced and a responsible manner. I furthermore take note of, and agree to adhere to the following conditions (where applicable):

a) I will schedule my research activities in consultation with the relevant Company or Organisation and research participants (where relevant);
b) I agree that involvement of participants in my research is voluntary, and that participants havea right to decline to participate;
c) I will obtain signed consent forms from participants prior to any engagement with them;
d) I will inform participants about the use of recording devices such as tape-recorders and cameras, and participants will be free to reject them if they wish;
e) I will honour the right of participants to privacy, anonymity, confidentiality and respect for human dignity at all times. Participants will not be identifiable in any way from the results of myresearch, unless written consent is obtained otherwise;
f) All interviews (recordings) will be transcribed verbatim and analysed as per conventional data analysis techniques (example(s) of interview transcript to be included in final dissertation)
g) I will adhere to the principles of rigorous data collection, analysis and interpretation consistent with the design of the study;
h) I will keep a data trail for possible auditing purposes as well as the safe keeping of raw data fora period of three years after publication of the results;
i) I will send the draft research findings to research participants before finalisation, in order to validate the accuracy of the information in the report;
j) I will not use the resources of the university when I am conducting my research (such as stationery, photocopies, faxes, and telephones) and
k) I will include a disclaimer in any report, publication or presentation arising from my research, that the findings and recommendations of the study do not represent the views of the Central University of Technology.
l) Aside from laboratory as well as consumables or materials supplied by the university needed to complete practical projects which might be central to my study (dependent on study field), I willnot use the resources of the University when I am conducting my research (such as stationery, photocopies, faxes, and telephones).
m) All practical artefacts produced in support of my study using the university's laboratories, consumables, and materials will remain the property of the University.
n) If I supplied my own materials and consumables, I will permit access to all practical projects or artefacts to the University for a period of three (3) years for exhibition purposes.
o) All data collected for the research (including, but not limited to, completed questionnaires; statistical analysis performed on the data; interview audio-files/transcripts; artefacts/audio- visual materials; documents) will be kept safe at a designated space at the university for a periodof at least three years. Computer files will be backed-up and password-protected.

I declare that all statements made in this application are true and accurate. I accept the conditionsassociated with the granting of approval to conduct research and undertake to abide by them.

STUDENT SIGNATURE / PROJECT LEADER SIGNATURE / SIGNATURE OF RESEARCHER	
DATE	21/08/2023

7. DECLARATION BY SUPERVISOR(S) (where applicable)

I/We declare that I/we shall oversee the student's adherence to all statements as set out above.	
SIGNATURE (Main supervisor)	**Dr LG Mollo**
SIGNATURE (Co-supervisor)	**Prof F Emuze**
DATE	23 August 2023

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APPROVAL OF FEBIT ETHICAL COMMITTEE (FRIC)

Please tick relevant decision and provide conditions/reasons where applicable			
Decision			***Please tick relevant option***
1.	Application approved		✓
2.	Ethical clearance number	FRIC:31/08/2023(2)	
3.	Application approved subject to certain conditions. ***Specify conditions below***		
4.	Application not approved***. Provide reasons for non-approval below***		
SIGNATURE: **Chairperson: Ethics committee**			
DATE	**31/08/2023**		

Cc Dean: FEBIT