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Improving the Health and Safety of Manufacturing Workers by Detecting and Addressing Personal Protective Equipment (PPE) Violations in Real-Time with the Use of Automated PPE Detection Technology

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ABSTRACT

Improving the Health and Safety of Manufacturing Workers by Detecting and Addressing Personal Protective Equipment (PPE) Violations in Real-Time with the Use of Automated PPE Detection Technology

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The Centers for Disease Control and Prevention (CDC) emphasized that Personal Protective Equipment (PPE) can significantly reduce the risk of occupational injuries and illnesses. However, improper use, failure to use, and other PPE-related violations can still result in injuries and fatalities. Eye and face protection violation has been one of the top 10 most frequently violated OSHA standards in fiscal years 2018, 2019, 2020, 2021 and 2022 consecutively. A common practice among safety professionals to ensure PPE compliance has been to physically inspect or monitor PPE usage among workers, which has been found to be unsustainable on a continuous real-time basis. While there have been efforts to investigate and recommend solutions to PPE non-compliance over the years, little effort has been made to the concept of continuous real-time PPE compliance monitoring among manufacturing workers.

This dissertation focuses on the use of automated PPE compliance monitoring systems in a manufacturing setting. The traditional method of PPE compliance monitoring, relying on human observation and review of recorded videos, is prone to human errors and limitations. This study aims to investigate the effectiveness of an automated system used in detecting PPE violations in real-time, and to evaluate its scope and limitations under various normal working conditions. Three major hypotheses were proposed, including the impact of worker training or experience on PPE compliance, and a comparison between an automated PPE detection technology (driven by Artificial Intelligence) and video recording with human reviews.

The objective of this study is to provide insights into the effectiveness of an automated PPE compliance monitoring system when compared to traditional PPE monitoring system which relies on human reviews of video recordings, and to inform the development of policies and systems to improve PPE compliance in real-time which can reduce injuries in the manufacturing industry. The findings of this study can contribute to the improvement of workplace safety and health in the manufacturing industry.

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Chapter 1: Introduction

1.1 Background

Manufacturing workers face various occupational hazards, including exposure to chemicals, gases, burns, cuts, lacerations, and flying objects, leading to potential hearing loss and other risks. The 2019 Bureau of Labor Statistics (BLS) workplace injury statistics, which ranked the most dangerous occupations (excluding fatal injuries), placed manufacturing third, following healthcare/social assistance and retail trade. The industry recorded 395,300 workplace injuries and 35,000 illnesses. Given that manufacturing typically involves handling objects and equipment in processes like assembly, shipping, and receiving, there's a heightened risk of occupational injuries for workers in this sector.

According to the BLS 2018 report, two major causes of workplace fatalities were interactions with objects and equipment, resulting in 786 deaths, and harmful substance or environmental exposures, causing 621 deaths. These figures highlight the broader issue of workplace accidents in the United States and internationally. The National Safety Council reported in 2010 that occupational accidents lead to 3.2 million disabling injuries and 9,000 fatalities each year, with an economic impact exceeding $110 billion. Further emphasizing this issue, 2018 data revealed about 164,127 preventable deaths and 46.5 million injuries in the U.S., incurring costs of nearly $1.06 trillion. The International Labor Organization in 2018 noted that over 500 workers worldwide lose their lives daily due to job-related accidents.

The primary concern of safety professionals is to reduce the incidence of industrial and occupational accidents and thus reduce the overall associated costs. To achieve this, they employ several control measures to mitigate and control hazards (injuries and illnesses) as outlined by the Occupational Safety and Health Administration (OSHA) and the National

Institute for Occupational Safety and Health (NIOSH), popularly called the Hierarchy of Controls. These hierarchy of controls from most effective and protective to least effective includes elimination, substitution, engineering Controls, administrative controls, and personal protective equipment (protecting the worker with personal protective equipment). Personal protective equipment (herein after referred to as PPE) is required by employers when elimination, substitution, and engineering controls do not work to totally eliminate hazards and when administrative controls are not feasible or do not provide adequate protection.

According to OSHA, PPE are devices worn by workers to minimize their exposures to specific hazards. Examples of PPE include respirators, gloves, eye, and face protections, cut resistant aprons, full body suit, hard hats, safety glasses, safety boots, and ear plugs among others. The proper and regular utilization of Personal Protective Equipment (PPE) plays a crucial role in mitigating the economic and financial burden associated with occupational injuries and illnesses. By adopting such safety measures, not only can a nation experience a reduction in the costs associated with employee turnover, but it also contributes to enhancing the health and longevity of its workforce. This approach, as highlighted by Tamara et al. in 2019, underscores the broader benefits of PPE usage that extend beyond immediate safety concerns to encompass long-term financial and public health advantages.

PPE is an essential component of any occupational safety and health program. As the last line of defense for protection of workers, PPE is one of the elements an organization should pay more attention to, since if they fail, the worker can suffer serious consequences. Afterall, it only takes one time or incident of PPE violation for a serious injury to occur.

1.2 Problem Statement

According to Santiago Barro-Torres et al. (2012), the primary challenge with a policy focused on Personal Protective Equipment (PPE) occurs when workers either fail to use PPE or use it incorrectly, whether intentionally or unintentionally. Enforcing the use of PPE in the workplace can often become a challenge for employers due to the unintentional and intentional non-compliance to the use of PPE by workers.

Each year, PPE helps to keep millions of employees safe at work, thus increasing productivity and reducing injuries and illnesses. Manufacturing companies comprise of establishments engaged in the mechanical, physical, or chemical transformation of materials, substances, or components into new products. To reduce the incident rate in the manufacturing industry, the application of technical and organizational actions is required. Among these actions, several of them include the application of PPE to prevent harm from uncontrollable risks.

However, despite the efforts of most employers and OSHA regulations/standards on PPE usage to workers in recent years, injury rates from exposures or contact with objects and equipment are still on the rise (BLS report, 2020). Notably, Eye and Face Protection (a component of OSHA required PPE) has in the past 5 years, been consecutively listed on OSHA's top 10 violations ascending from the 10^{th} position (in 2018) to the 8^{th} position (in 2021) and currently at 9^{th} position (2022). The Fiscal Year (FY) 2018 was the first time ever that PPE violations (of any type) made it to OSHA's top 10 most frequently cited violations. NIOSH reports that every day, about 2,000 U.S workers sustain job-related eye injuries that require medical treatment. However, safety experts and eye doctors believe that the right eye protection device can lessen the severity or even prevent 90 percent of these eye injuries.

Previous research endeavors and publications on PPE compliance have identified factors that impact the use or non-use of PPE in the workplace (especially in the construction company) and proffered various solutions to include management support, improved gear (for comfortability and functionality), signage, training, and monitoring (which is one usually neglected intervention in improving PPE compliance.). In a study by (Daugherty et al 2009), the belief that PPE usage poses an inconvenience led to an increase in self-reported non-compliance. But on the other hand, the perceived reprimand for non-compliance with PPE usage significantly increased the odds of self-reported compliance. Thus, encouraging monitoring for PPE usage by supervisors increases the odds of PPE compliance.

Currently, most manufacturing companies rely on the use of traditional PPE compliance monitoring systems that involve the use of physical inspection of PPE usage on production floors by a safety professional or assigned personnel. According to Santiago et al. (2012), this solution is assumed ineffective since most workplaces rely on visual inspections by safety professionals (or assigned persons, often performed at intervals), and does not allow for the performance of continuous PPE real-time monitoring and traceability in an industrial setting.

Shi Chen et al., (2020) posited that traditional methods of occupational safety monitoring, typically conducted by on-site or off-site observers, heavily depend on human observation, which may not be entirely reliable for worker protection. This is due to inherent human factors and errors, such as mistakes made unintentionally, poor judgment, flawed decision-making, and disregard for established procedures. These limitations highlight the need for more robust and objective safety monitoring methods to effectively safeguard workers in various occupational settings. Moreover, observers responsible for monitoring PPE usage face practical limitations: they cannot be simultaneously present in multiple locations, are unavailable around the clock, and are susceptible to human fallibility, which may lead to oversights in safety monitoring. This has prompted the need to develop an automated system of PPE compliance monitoring.

Few researchers have advocated for the use of a form of video surveillance system commonly called Closed-Circuit Televisions (CCTVs), both the “basic systems and systems with a degree of intelligence” Paola et al., (2016). Most of the AI-driven PPE monitoring systems proposed in these studies were designed for use in the construction industry where injury rates are higher and employee supervision is almost impossible. The systems mostly rely on feeding captured images of construction workers into a PPE detection system and running the algorithm to identify workers who had PPE on and who do not have PPE on. In safety and health, these are categorized as lagging indicators where PPE violations are determined after the incident has already happened with the potential of an injury already occurring. The PPE monitoring systems developed have limitations, and adaptability for large scale use is discouraged (this will be discussed extensively in the literature review section). But despite these innovations, there has been no study to determine the viability and long-term effectiveness or not of fully automated PPE compliance monitoring system in contrast to the use of an ordinary video surveillance (CCTV recording) in detecting PPE violations in the U.S manufacturing industry.

This project seeks to understand how an automated PPE monitoring system can assist in improving PPE compliance amongst workers in a manufacturing setting in real-time: A comparison between an automated PPE detection device and a video recording reliant on the human reviews.

1.3 Hypotheses

Hypothesis 1: Variables such as PPE training, consequences for PPE violations or experience (tenure) of workers have no significant effect on PPE non-compliance related injuries among manufacturing workers.

Hypothesis 2: Manufacturing environment that uses automated PPE detection devices do not record fewer PPE violations than manufacturing environment that uses video recording (with the aid of raters/reviewers) within a set time frame under certain treatment conditions, such as lighting, worker posture, worker position, distance of worker to camera, male or female workers, view of worker to camera, presence of an obstacle (plexiglass in between the camera and the worker).

Hypothesis 3: There is no significant difference in the time it takes for an automated PPE detection device to detect PPE violations in real-time and the time it takes a video recording reviewer to detect PPE violations under certain treatment conditions such as lighting, worker posture, worker position, distance of worker to camera, male or female workers, view of worker to camera, presence of an obstacle (plexiglass in between the camera and the worker).

1.4 Objectives

This study has the following objectives:

1. To investigate with the use of a survey, the factors and current trends of PPE non-compliance in a manufacturing setting, and the most common PPE violations in the manufacturing workplace (assessing manufacturing industries' most used PPE - Safety Glasses, Safety Gloves, Hearing Protection, and Respiratory Protection).

2. To investigate the scope and limitations of automated and manual PPE detection technologies in identifying PPE violations in a manufacturing setting. We hope to evaluate the PPE detection technologies under different conditions, such as lighting, worker posture, worker position, distance of worker to camera, male or female workers, view of worker to camera, presence of an obstacle (plexiglass in between the camera and the worker).

3. To examine if an automated PPE detection device is effective in detecting PPE violations in real-time. It is hoped that these findings will help safety professionals in

formulating systems and policies geared towards improving PPE compliance, thereby reducing violations and injuries arising from PPE non-compliance.

Overall, this study will aid opportunities to understand and identify PPE violations in the workplace. This will also better inform safety professionals about the best methods to detect PPE violations and about common trends in the manufacturing industry. It also aims to gain better understanding of the benefits and effects as well as the limitations associated with the use of automated video monitoring technology as a means of improving PPE compliance in manufacturing companies in the United States.

Chapter 2: Review of Literature

2.1 What is Personal Protective Equipment?

PPE are devices worn by workers to minimize their exposures to specific hazards. Examples of PPE include respirators, gloves, eye, and face protections, cut resistant aprons, full body suit, hard hats, safety glasses, safety boots, and ear plugs among others.

Different forms of hazards exist in every workplace, they could be in the form of sharp edges, falling objects, slips and falls, cuts and lacerations, flying sparks, chemicals, noise, and a host of other potentially dangerous situations which could lead to injuries and illnesses. The Occupational Safety and Health Administration (OSHA) requires that employers must protect their workers from inherent workplace hazards that can lead to injuries and illnesses. Controlling hazards at the source is the best way to protect employees. OSHA recommends the use of engineering control to manage or eliminate hazards to the greatest extent possible. "For example, building a barrier between the hazard and the employees is an engineering control; changing the way in which employees perform their work is a work practice control" (OSHA Publication, 2004). While elimination, substitution and administrative controls are often considered as the most effective form of hazards controls, OSHA requires the use of PPE (Personal Protective Equipment) to reduce employee exposure to hazards when engineering and administrative controls are in-effective to eliminate the hazards.

It is useful to consider that exposures in the workplace are typically preventable by using engineering controls (example, improved ventilation) and administrative controls (example, mandating the use of non-hazardous chemicals and appropriate housekeeping) or the use of PPE to create a barrier between the worker and the exposure (Wall, 2009).

2.2 OSHA Requirement on PPE

According to OSHA, in order to provide maximum protection for workers in the workplace and ensure a safe and healthy work environment, it requires the active collaborative efforts of both the employer and employee. 29 CFR 1910.132 generally stipulates that employers are responsible for:

- Performing a "hazard assessment" of the workplace to identify and control physical and health hazards.
- Identifying and providing appropriate PPE for employees.
- Training employees in the use and care of the PPE.
- Maintaining PPE, including replacing worn or damaged PPE.
- Periodically reviewing, updating, and evaluating the effectiveness of the PPE program.

In general, employees should:

- Properly wear PPE,
- Attend training sessions on PPE,
- Care for, clean and maintain PPE, and
- Inform a supervisor of the need to repair or replace PPE.

2.3 OSHA Regulations on Industry Specific Personal Protective Equipment

Highlighted below are OSHA regulations that require employers to provide PPE to workers, conduct hazard assessment to identify and control physical and health hazards, carefully identifying appropriate PPE for workers, training employees in the use and care of PPE, PPE maintenance, and periodic review and evaluation of the PPE program. 29 CFR 1910.132 – 138, highlights the PPE standards for general industry: 29 CFR 1926.95 – 102 highlights the requirements for PPE in the construction industry: while 29 CFR 1915.152 – 157 highlights the requirements for PPE in the maritime industry.

2.4 Benefits of Correct and Effective Use of PPE

Tamara et al. (2019) state that the consistent and proper utilization of personal protective equipment (PPE) will contribute to the mitigation of the economic and financial repercussions of occupational maladies and injuries on the country, the reduction of employee attrition expenses, and the enhancement of the health and longevity of the workforce. PPE contributes to the safety of millions of workers annually, thereby enhancing productivity and reducing the incidence of ailments and injuries (BLS Report, 2018). In order to mitigate the occurrence of injuries and ailments within the manufacturing sector, it is imperative to implement both technical and organizational measures. Some of these measures consist of donning personal protective equipment (PPE) in order to avert damage caused by uncontrollable hazards.

PPE can save a worker's life in several ways, only if worn properly, consistently, and appropriately. Increased compliance with PPE usage can result in decreased injuries and recordables, which in turn leads to fewer workers' compensation claims and running costs, which translates to increased cost savings for employers. Although the extent to which PPE non-compliance economically impacts a business has not been fully studied in the U.S. manufacturing environment.

Kimberly-Clark Professionals, in their 2012 survey of safety professionals found high incidence of PPE noncompliance in the workplace among U.S. workers. Of the 110 safety professionals that were surveyed, 82 percent admitted to having observed workers in their organization failing to wear required PPE during the previous year. Of the respondents, 85 percent of them claim to have company safety programs in place. Of this number, 69 percent said the program had helped reduce reportable incidence rates, and 58 percent said incidents had greatly decreased by 50 percent or more.

The most significant costs to businesses resulting from PPE non-compliance, according to a 2019 white paper titled "Overcoming the barriers of PPE compliance with the use of artificial intelligence" published by Cortexica (a vision AI company based in the United Kingdom), are injury claims, inefficiencies caused by injured and absent workers, and the purchase of new equipment. Five percent of businesses with a high-risk work environment incurred losses exceeding £1,000,000 ($1,257,900) and thirty percent incurred losses exceeding £250,000 ($314,480) in the preceding year as a result of PPE non-compliance, according to the report. Additional emphasis is placed on the report's finding that over 25% of the injuries resulting in work absences could have been averted had employees adhered to PPE regulations.

PPE considerably increases occupational safety and, by extension, workplace productivity, which is critical in any business environment (Mohamad et al., 2014; Suchardova and Sucharda, 2013), as stated by Mohamad et al. (2014). From OSHA's records of PPE citations/violations, and company records of PPE violations that led to first aid injuries, beyond first aid injuries and recordable/reportable injuries and illnesses, safety experts and risk managers believe that PPE non-compliance have significant negative economic impact on businesses.

2.5 Previous Literatures and Current Trends on PPE Compliance Detection using Advanced Technology and traditional PPE compliance measures.

OSHA states that Personal Protective Equipment (PPE) is gear worn by workers to protect them from certain workplace hazards. Proper and consistent use of PPE can help reduce the economic impact of work-related injuries and illnesses, lower employee turnover costs, and improve the overall health and well-being of the workforce (Tamara et al., 2019). In simpler terms, wearing the right protective gear at work keeps employees safe, saves money, and promotes the overall health of workers.

According to the National Safety Council, occupational accidents cause millions of disabling injuries and thousands of deaths each year, resulting in a staggering cost to society. In 2018, the United States alone witnessed over 164,000 preventable deaths and 46.5 million injuries, with costs exceeding $1 trillion. Shockingly, the International Labor Organization reports that work-related accidents claim the lives of over 500 individuals, devastating families and impacting the economy. These statistics underscore the significant toll of workplace accidents on individuals and society, highlighting the urgent need for improved safety measures.

The Centers for Disease Control and Prevention (CDC) highlighted that PPE can significantly reduce the risk of occupational injuries and illnesses. However, improper use, failure to use, and other PPE-related issues can still result in injuries and fatalities (Sehsah et al., 2020). In 2018, the Bureau of Labor Statistics reported that out of 2.8 million nonfatal workplace injuries and illnesses, approximately 194,000 involved head injuries, and 170,000 involved eye injuries. Additionally, the improper use of PPE was one of the top 10 most frequently cited OSHA standards violated in fiscal years 2018, 2019, 2020, 2021 and 2022 consecutively. OSHA provides resources on PPE, including standards, training materials, and guidance on selecting and using PPE.

A research study published in the National Library of Medicine found that approximately 60% of workers wear Personal Protective Equipment (PPE) while on the job. However, many workers choose not to use PPE due to reasons such as discomfort, lack of knowledge, and ill-fitting gear. The study revealed that 64% of workers experienced different types of occupational accidents in the last 12 months including being hit by falling objects, falling from heights and tool-related accidents. It's important to highlight that the effectiveness of PPE largely depends on using it correctly and maintaining it properly. The study recommended that employers should prioritize providing training and education on the proper use of PPE to ensure the safety of their employees. (Sehsah et al., 2020).

For the past five years, PPE violations (eye and face protection) have emerged as a significant problem, breaking into the top 10 OSHA violations consistently. While PPE compliance remains an issue, researchers have in recent years identified factors that influence PPE compliance. PPE non-compliance could lead to an increased worker's compensation and higher insurance premiums, thereby impacting the business negatively. According to previous research and surveys, there is a high rate of PPE noncompliance nationwide. A survey in 2008 polled by the National Safety Council, revealed that 89% of safety professionals admitted to witnessing a worker's failure to wear PPE in necessary situations.

In the past, few studies have been carried out by research firms and researchers on the factors that affect the use of PPE in the workplace. These studies have assessed factors in several occupations to determine which barriers hinder them from wearing PPE or complying with appropriate and consistent use of PPE in the workplace. These barriers include unavailability of the equipment, discomfort of the equipment, interference with job skills, and being too expensive. Research conducted by Cavazza and Serpe (2009), Lombardi et al. (2009), and Olson et al. (2009) has echoed findings from the 2008 IOM report regarding organizational factors influencing PPE use. These studies emphasize elements such as the availability of PPE, engagement in training and refresher courses, the influence of supervisors and peers in using PPE, and the level of organizational support for worker safety and health. This includes how effectively a company reduces hazards and prioritizes safety objectives, underscoring the multifaceted approach needed to encourage proper PPE use in the workplace.

Support is also evidenced by senior managers' encouragement of safety practices and the level of encouragement for worker participation in health and safety discussions, positive reinforcement of individual compliance behavior, and negative reinforcement (e.g., verbal warnings). The study by Kimberly-Clarke in 2012 also cited factors for noncompliance by respondents to include uncomfortable PPE, PPE being too hot, blamed PPE for decreased production or inability to perform tasks, unavailability of PPE near the work area, ill-fitting PPE, and unattractive PPE.

As part of solutions to the issue of PPE non-compliance, common recommendations by safety and health professionals and other experts include management support, improved gear (for comfortability and functionality), signage and monitoring. In the survey by Kimberly-Clark professionals, the most popular strategies taken by safety professionals to encourage greater PPE compliance were to improve existing PPE education and training (61% of respondents), increase monitoring/supervision of employees to ensure compliance (48% of respondents) as well as attribute compliance to performance evaluation, purchasing stylish and more comfortable PPE and developing incentive programs.

While PPE training has been recommended to ensure workers' safety by researchers, it is important to also consider the use of PPE monitoring systems as a solution to the issue of PPE compliance. In a recent research publication, PPE monitors (health care workers) were trained and assigned to physically monitor how workers in their unit don and doff PPE during their work shifts. In the survey used in the publication, 68% of the respondents agreed or strongly agreed that "PPE monitors played an important role in keeping staff safe". However, reliance on unit staff as monitors and sustainability of the process was a major limitation (Summerlin-Long et al., 2021). In a similar study conducted by the CDC in 2022 on the guidance on PPE used by health care workers in infectious disease units, they also advocated for the use of a trained observer who will coach, monitor, and document successful donning and doffing of PPE by workers. However, it was recommended that in order to reduce the possibility of an infection by healthcare workers, glass-enclosed rooms, or other designs (like wide glass doors, windows, video monitoring) to observe ongoing care in the patient room and activity in the PPE doffing area are preferred. (CDC, 2022).

More recently, the global health crisis with the emergence of the novel coronavirus (COVID-19), triggered a global emergency in the use of respiratory protective equipment with high risk and unprecedented disruptions. It has become imperative to ensure the health and safety of people in the hospitals, factories, offices, stores, in public and everywhere they can be susceptible to the virus, with the use of various kinds/types of face masks/face shields (commonly referred to as PPE).

PPE for the purpose of this research project does not include equipment used in the protection against COVID-19. The use of face covering is now strongly recommended by every health and safety agency, bodies, organizations, government health authorities and even the World Health Organization (WHO). Identifying non-compliant cases and ensuring a timely response to such situations is, however, critical. It is also worth knowing that the rise in PPE violations in most industries in the last few years has increased awareness to the need to pay closer attention to PPE compliance and enforcement in the work environment.

Wong et al. (2020) in their study on the critical factors for the use or non-use of personal protective equipment amongst construction workers, cited that safety supervision and safety training were part of the reasons why construction workers use PPE. Regular monitoring by safety supervisors at construction sites can enhance PPE usage among workers, primarily due to the supervisors' focus on safety concerns. This increased attention to safety measures can lead to a corresponding decrease in the frequency of accidents at construction sites, showcasing the vital role of consistent and proactive safety supervision in promoting workplace safety and reducing risks (Wong et al., 2020). Man et al. (2017) reported that safety supervision and safety training influence the risk-taking behavior of construction workers. Safety supervision in their study refers to the frequency and thoroughness of inspection by management on construction workers' unsafe behaviors and working condition (Jiang et al., 2014).

Before now, the most adopted solution to PPE monitoring to ensure compliance is through visual inspection by safety professionals (sometimes called safety monitors) or assigned personnel. However, this solution has proven to be ineffective, since visual inspections can only be performed at specific times and consecutively across most workplace and does not allow for the performance of PPE real-time monitoring and traceability on a large industrial scale. A recent Cortexica (a leader in artificial intelligence, machine learning, and video analytics) survey found that 84% of businesses rely on a manual checking system for the proper use of PPE.

PPE monitoring technology has been mentioned in a few research and journals as part of factors that improve PPE compliance in the workplace especially in the construction industry. But there has been no study carried out to specifically determine the effects and differences between automated PPE monitoring technology versus video recording (requiring human review) to help improve PPE compliance among manufacturing workers in the United States. This study will provide information which will be useful to drive policies to reducing PPE non-compliance related injuries and illnesses. Hence, the reason for this research endeavor.

2.6 Technological Interventions to Improve Occupational Safety Management and Promote PPE Compliance Monitoring

Barro-Torres et al. (2012) introduced a solution for real-time personal protective equipment monitoring by integrating smart devices into clothing. This innovation is situated within the domains of wearable computing and cyber-physical systems (CPS) and utilizes radio frequency identification (RFID) technology. A system that incorporates various forms of networks and technologies was described in the paper. An example of this is a mesh network, which facilitates communications and offers a live update on the whereabouts of employees and their personal protective equipment. Conversely, it is mandatory for every employee to possess a

Body Area Network (BAN) or personal network device (incorporated into the PPE) that is capable of determining the whereabouts and presence of the utilized PPE. Nevertheless, a number of issues were brought to the solution's attention.

These included the power consumption of individual devices (requiring daily battery recharges), the development of a wireless installation consisting of multiple relays to cover the designated areas, and unintended scenarios in which a worker's device malfunctions (such as coverage loss, device failure, or improper handling). They reached the conclusion that data collection was rendered erroneous and challenging due to loss of coverage, device failure, and improper device handling; consequently, credible decision-making regarding PPE compliance, which was the primary objective of designing the devices/system, was not influenced.

Further investigation was conducted by Balakreshnan et al. (2020) concerning the utilization of artificial intelligence in learning factories to detect PPE compliance. The project showcased the utilization of Machine Vision (MV) and Artificial Intelligence (AI) to detect personal protective equipment (PPE), specifically safety eyewear, in simulated hazardous zones of the learning factory. The aim of the project was to develop and execute an automated system that could guarantee the well-being of individuals while they are in close proximity to apparatus that may cause ocular hazards. A laboratory-based conformance detection system for protective eyewear was developed in this study utilizing Internet of Things (IoT) devices and artificial intelligence (AI). Although the research yielded quite encouraging results, it was not devoid of obstacles and constraints.

The study investigated two versions of the AI vision model that provided support. In the initial iteration, model training was exclusively conducted using PPE images acquired from a Google database. The study conducted by Balakreshnan et al. (2020) concluded that the overall performance of the model was inadequate, rendering it completely unsuitable for implementation in a safety system. The base model, in particular, encountered "significant difficulties in detecting safety glasses in general and was unable to detect glasses beyond an impracticably small focal distance" (Balakreshnan et al., 2020). An enhanced model was implemented in the second iteration, wherein the system was exclusively trained using images acquired from the laboratory setting. In comparison to the initial iteration, the outcomes demonstrated an increase of 155% in the overall precision model, 79.1% in recall, and 233% in the mean average precision. While there is an enhancement in overall performance when compared to the foundational model, these figures remain comparatively modest in the context of applications that require PPE compliance detection.

The implementation of AI and IoT has the capacity to enhance workplace safety through the provision of an automated method for preventing and monitoring injuries. This algorithmic system operates autonomously, devoid of human intervention, by utilizing widely accessible software and hardware components.

By integrating Machine Learning (ML) and Artificial Intelligence (AI), a vision-based safety system that operates in real-time can be established. This system would have the ability to identify and document both present and prospective safety infractions, encourage adherence to regulations, and ultimately avert unanticipated catastrophes. Automated electronic surveillance is implemented to maintain audit traces of actions, facilitate prompt responses to instances of non-compliance, and ensure real-time compliance. By simultaneously detecting various types and models of personal protective equipment (PPE) and providing real-time incident/violation data for analysis, the system can be utilized to suggest corrective/control measures in the event of safety breaches/violations in the context of PPE compliance.

2.7 The Concept of the Hawthorne Effect

The concept of the Hawthorne Effect, which originated from a collection of investigations carried out by Elton Mayo and his colleagues during the late 1920s and early 1930s, pertains to the behavior modification that occurs when individuals become cognizant of being observed. Mayo and his team conducted these investigations at the Western Electric Hawthorne Works in Chicago, with the objective of determining the impact of various work conditions, including break times and illumination, on employee output.

At the outset, the researchers made the observation that seemingly every alteration in the work environment, including improvements in illumination, resulted in an apparent surge in productivity. Nonetheless, productivity increased once the modifications were reversed. Upon reflection, it became clear that the workers' perception of being observed and valued was significantly impacting their behavior, and not the physical changes themselves. During the course of the study, it was the workers' focus that increased their productivity, not the modifications to the work environment.

Significant implications of the Hawthorne Effect extend to both research and managerial decisions at work. It emphasizes the significance of psychological and social factors in the workplace, as well as the influence that employees' perceptions of being valued and researched can have on their conduct. Both the areas of human resources and the discipline of industrial psychology have been impacted by the effect, which emphasizes the importance for businesses to focus on their employees in addition to the tangible work environment. This comprehension has played a crucial role in influencing contemporary methodologies regarding workforce efficiency and the dynamics of the workplace.

Chapter 3: Methods

3.0 Introduction

In this study, we investigated a key area of occupational safety and health in the manufacturing industry, concentrating on the role of Personal Protective Equipment (PPE) and the significance of automated detection technology in ensuring compliance in real-time. The study is centered on a number of hypotheses and objectives which aim to explore the effects of real-time PPE violation detection and certain factors that influence PPE compliance among manufacturing workers.

Hypothesis 1 investigates if variables such as PPE training, worker's tenure, age, and consequences for PPE non-compliance significantly impacts PPE non-compliance related injuries in the workplace. It queries the assumption that older, better trained, and more experienced workers (to name a few) are more likely to adhere to PPE regulations. This hypothesis (through the aid of a questionnaire) will not only examine the current trends in PPE non-compliance but will also provide an insight on the particular PPE type (safety glasses, gloves, hearing, and respiratory protection) that are most often neglected or misused.

The second hypothesis compared the efficiency of two types of PPE compliance monitoring systems to detect more or fewer PPE violations under certain treatment conditions: an automated PPE detection system and the other utilizing human review of a video recording. The hypothesis suggested that there will be no significant difference in the number of PPE violations detected by these two systems when conditions such as lighting, worker posture, distance and other typical workplace factors are influenced. This will aid in understanding if automated PPE detection systems presents superior alternatives to human video reviews.

The third hypothesis tested the response time of the automated PPE detection system to make an inference on PPE compliance or non-compliance, anticipating that when compared to the response time of a human reviewer watching video footages, there will be no significant difference in the time (in seconds) it takes to detect PPE violations in a simulated manufacturing environment. This part of the study evaluates the impact of deploying automated PPE detection systems in a real-world manufacturing environment where real-time PPE violation detection is crucial for preventing accidents and injuries.

The main objective of the study was to probe the real-time effectiveness of automated PPE violation monitoring systems. If proven to be reliable for real-time detection of PPE violations, such technological innovations could become a key component of safety programs, providing immediate feedback and PPE enforcement that could significantly improve PPE compliance, reduce violations and subsequent injuries. In addition, the study aimed to investigate the scope and limitations of automated PPE detection technology under certain treatment conditions which includes environmental and operational conditions which are identical to working conditions in manufacturing settings. By exploring these objectives, the study aimed to improve the health and safety of manufacturing workers in the United States by using real-time automated PPE monitoring systems.

3.0.1 Summary (Methodology)

This chapter outlined the procedures as well as data analysis methods used in the conduct of this research. The study involved the combination of the use of Qualtrics survey/questionnaire and a designed laboratory experiment. The chapter is divided into 3 phases.

1. **Phase 1** highlights the procedure for the design and deployment of a research survey which aims at understanding existing PPE compliance challenges inherent among

workers in the manufacturing industry (as classified by the North American Industry Classification System - NAICS) . Four (4) commonly used PPE in the manufacturing industry were selected and included in this survey based on findings from previous literature. They include OSHA compliant safety glasses, respiratory protection devices (an N95 mask), safety gloves and hearing protections. Also included in this phase are the data analysis methods used in interpreting findings from the Qualtrics survey.

2. **Phase 2** describes the automated PPE detection device, selected PPE equipment under investigation, as well as other technologies included in this research. It includes a pilot study to test how the device works and how it was used for the purpose of this research as well as its limitations. The device pilot study was carried out at the West Virginia University's (WVU) Lane Manufacturing Innovation Hub at the Statler College of Engineering and Mineral Resources. At the end of the pilot study, a descriptive analysis of findings (the scope and limitation of the devices) was documented and formed a basis for the actual lab simulation/testing for phase 3.
3. **Phase 3** includes the final lab testing of the automated PPE violation detection device and a video footage recording in a simulated manufacturing environment with actors (volunteers) carrying out tasks under certain conditions like those performed by manufacturing workers in the real world. The goal is to see if there is a significant difference in the number of PPE violations reported by the automated PPE detection technology and the number of violations reported by the video recording reviewer. Also, a significant objective is to compare the time it takes to make an inference on PPE violation detected, or no violation detected between the automated PPE detection device and a video footage reviewer.

3.1 Survey (Phase 1)

Data was collected through a cross-sectional survey, designed with the aim of understanding the current trends in PPE violations, effects of certain variables contributing to PPE violations, and identifying current PPE compliance monitoring practices in a manufacturing setting. The survey was designed and distributed through Qualtrics (online, with link sent to participants via email, text messaging, and social media broadcast) to about 60 safety professionals (persons who are directly responsible for the health and safety of workers based on related job titles and years of experience) from West Virginia University safety management listserv of past and present students who qualify as one, as well as industry experts in the manufacturing industry.

Survey questions are close ended with multiple choice answers (“Yes or No”) and Likert scale choices (ranging from “Yes, Always to No, Never”). This is to ensure that we have a set of discrete responses rather than infinitely variable responses. In the survey, we asked questions relating to PPE non-compliance prevalence in the workplace. The survey questions were divided into 8 sections with a total of 64 questions:

1. Demography.
2. PPE violation records.
3. Workplace PPE policy.
4. PPE Training.
5. PPE Related Injuries
6. PPE violations based on age and tenure (years of current work experience) of the workers.
7. Consequences for PPE violations.

8. PPE violations monitoring.

3.1.1 PPE Survey Pilot Test

A pilot study of the survey was carried out and responses analyzed from 3 respondents. Graduate students of the MS safety management program at West Virginia University were randomly selected to take the survey and provide feedback and critique of their experience in easily comprehending and completing the survey questions. Some of the feedback and critique listed below were taken into consideration and adopted in the design of the final survey deployed to industry participants.

Feedback 1: "The survey was great to participate in, it included all detailed questions about PPE and how they are being used during work. In addition, it's better to have multiple choice questions rather than writing essays, this shows that the survey was structured well with the PPE questions. The survey went smoothly and questions about PPE would give broad flexibility in data analysis".

Feedback 2: "My first impression of the survey was that it was very straight forward and easy to follow. The first page was very descriptive of what to expect including time to complete and I liked the transparency. Some questions might have multiple answers too, but I'm only allowed to choose one answer. For example, what days have most incidents, or what time of the shift, etc. And I'm not sure if multiple answers might mess with the data you're looking for, but it is just something I noticed. Some questions have options 1,2,3,4 and "I don't know" If I was a supervisor filling out that form my answer might be "none of the above" but I will be forced to either choose I don't know, wrong option, or leave it blank. For example, "Which of these PPE violations occurred the most in your plant?", my answer might be "none" or "other". Another thing was on the 3rd or 4th page there is a question/title that was not written down but instead says "Click to write question text". Other than that, the survey was very well organized, and the questions were very simple to understand from the first read. The font and size for me were perfect but I'm not sure if you can control those in the first place."

Feedback 3: "The survey was very user friendly I had no issues completing it. It had good background questions about the participants. They were good, detailed questions. I like that there was an option of "I don't know" because it will be hard to remember everything that happened at the facility without looking into the records. I really liked the question about what days of the week and what time most violation occurred, which may indicate something wrong happening at specific times. I think the survey is really good and has a lot of questions that will help in improving the workplace in a very positive way, I enjoyed completing the survey it was very interesting."

After the questionnaire was finalized, it was deployed and sent to safety professionals in the manufacturing industry for a period of 5 months electronically via emails, WhatsApp messaging, LinkedIn, and text messages, after which results were examined for completion and cleaned-up for data analysis. Out of over 60 participants that received the survey link, 41 participants responded to the survey, and only 31 out of those 41 respondents completed the survey at a 100% rate. This represents a 68.3% response rate for participants that responded. For the purpose of this research, we filtered out the incomplete responses, hence we only analyzed the data from the 31 respondents with a 100% completion rate.

The questions asked in the survey addressed various topics including safety professional's perception of PPE violation prevalence in their workplace; most common PPE (based on the 4 selected PPE types for this survey) violation in terms of days of the week and period of day with the most PPE violation; severity (first aid and beyond first aid) of injuries caused by PPE compliance violations; current methods/interventions employed to ensure PPE compliance and their effectiveness; potential solution to improve PPE compliance; and their perception on the use of technology to continuously monitor PPE compliance in real-time as a viable solution.

3.1.2 Statistical Analysis

A descriptive analysis (using proportions and percentages etc.) of data collected from the survey was performed to predict different variables influencing the prevalence of PPE violations among different groups of manufacturing workers.

The primary outcomes of these analysis are percentage of overall PPE violations that resulted in injuries (first aid and beyond first aid); percentage of specific/individual PPE violations that resulted in injuries (first aid and beyond first aid) based on the 4 selected PPE for this study; percentage of total observed PPE violations; percentage of PPE violations observed amongst the different age categories (less than 25, 25-49, and 50 or more), and percentage of PPE violations observed amongst workers in the different tenure categories (less than one year, 1-4 years, 5-10 years, and more than 10 years.

3.2 Testing the Scope and limitation of the Automated PPE Detection Device in a Lab Setting (Phase 2)

Next, we conducted a pilot study/lab simulation at the IMSE graduate lab (ESB B02) under the supervision of Dr. Omar Al-Shebeeb. This is to examine how the PPE detection device works using volunteers. Effort was also made to video record a real-life manufacturing process at the WVU Lane Manufacturing Innovation Hub (ESB G86). A worker was recorded while grinding a piece of aluminum using an industrial milling machine. This worker was provided a research volunteer consent form to review and sign and we ensured they had the right PPE on (safety glasses) before simulating the process. A video of sharp aluminum debris/particles flying around the worker was captured. This was used to analyze and select the best combination of factors that influence the performance of the automated PPE detection device to be used for the experiments. It also proved that the use of appropriate PPE in the manufacturing environment is critical to the safety and health of workers, and thus must be enforced.

After the video recording, the automated PPE detection and video recording devices were installed at the IMSE Graduate lab (ESB B02) with their individual cameras placed on a tripod stand about 7 feet high to overlook the simulated manufacturing work zone designed for the study. The work zone comprised of a 3 ft flat top table and a Computer Numerical Control (CNC) milling machine placed on it. The automated PPE detection device was pre-trained (using machine learning, algorithms, and machine vision) with over 3,000 images and videos of safety glasses, safety vests, helmets and N95 masks. This training (using machine learning) enabled the device to correctly identify specific types of PPE used in the study (consistent with those used in the manufacturing industries) under normal working environment and record PPE violations on instances it is unable to accurately detect any PPE based on certain conditions.

From the pilot study, it was discovered that the cameras (Logi 920) used in this study have a wide range of coverage of up to 12 ft with the ability to show facial features (like eyes, nose, mouth, and ears) vividly/clearly at such a distance without zooming. Recordings/images captured more than 12 ft will require zooming in on the pictures to vividly identify facial features.

The PPE detection device runs on BrainFrame software, a powerful, open, and smart vision platform, which is designed to be an easy to use and powerful Intelligent Video Analytics (IVA) solution for developers. BrainFrame has undergone complete optimization for seamless integration with the Intel IoT platform. It comes pre-integrated with Intel OpenVINO, ensuring enhanced performance and efficiency. Moreover, OpenVINO optimized models are readily available in the OpenVisionCapsules format, allowing for effortless utilization.

BrainFrame software empowers edge computing devices to perform video processing and AI inference tasks with the use of an external camera. It efficiently extracts real-time insights from stationary cameras, enabling continuous monitoring, tracking, and analysis. Its capabilities encompass a wide range of functions, including recognizing and tracking individuals, counting people and vehicles, zoning, monitoring traffic, classifying objects, conducting behavior analysis, and generating incident alerts, among others. BrainFrame produces structured data in graphical reports, statistics reports, and real-time alarms/cards. It offers pre-built smart vision applications for administration, industrial, retail, and safety compliance purposes, eliminating the need for development. This software was used in the development of the automated PPE detection device used in this study.

For the purpose of this study, a personal use automated PPE detection system was developed by an internet of things expert. Due to lack funds for the study, we could not acquire or design an integrated system that could automatically detect PPE violations in real time and at the same time log the number of recorded violations in structured graphical and statistical reports. So, we restricted the scope to only detect PPE violations, using the onscreen display of the violation count detected for analysis.

The device, upon detecting an object through the connected camera, works by first detecting if the object is human or not, within approximately 1000 milliseconds (approximately 1 second). Then it detects body parts where the trained PPE is supposed to be worn within approximately 2000 milliseconds (2 seconds). Once it can detect the necessary body parts accurately, it then detects the PPE worn, whether it's the correct PPE or not. This happens within 4 seconds of the worker (actor) walking into the camera frame. On instances where the automated PPE detection device cannot accurately determine if an object is a PPE in use in this study due to a combination of conditions, it records them as PPE violations. A log of the current person(s) detected, and the total number of violations detected is displayed on-screen on a continuous basis. This process continues to be automatically updated for the entirety of the period the device runs.

The lab simulation involved testing both the automated and manual PPE detection devices in detecting PPE violations under select working conditions which are similar to the normal working conditions of workers in an actual manufacturing environment. For the purpose of this study, only four (4) PPE will be tested, specifically, OSHA compliant safety glasses, NIOSH compliant N95 mask, a safety vest, and a helmet. The PPE detection device will be reset after every experiment is performed. This is to take the total number of people count back to zero (0) to avoid over or under estimation.

During this pilot study, we identified seven factors that could potentially affect the ability of the automated PPE detection device to accurately detect PPE violations as specified by the device developer. Seven of those factors will be used during the actual lab experiment. They include lighting, worker posture, worker position, distance of worker to camera, gender (male or female), view of worker to camera, presence of an obstacle (plexiglass in between the camera and the worker).

3.2.1 Testing Volunteer Recruitment, Consenting and IRB Approval

For the simulation of real-life manufacturing work process scenario, an experienced manufacturing worker (WVU Manufacturing Innovation Hub lab supervisor) was recruited. The choice of this volunteer was based on his extensive previous and active experience in the manufacturing industry and at the WVU manufacturing innovation lab where they perform real-life manufacturing processes similar to industry standards as full-time employees of WVU. Two other volunteers were recruited from WVU (current graduate students) to participate in the lab PPE violation experiments. They were trained and given consent forms to sign up as voluntary participants for the study. The consent form included a statement of confidentiality and suspension of any form of reprimand/discipline stemming from PPE violation acting during the simulated work process.

The study was approved by the WVU IRB with protocol number 2208621455 and was categorized as “Not Human Subjects Research (NHSR)”, since there will be no identifying information used for the purpose of this research.

3.2.2 List of Equipment Used

Below is a list of equipment used for this research.

1. UP Squared AI Edge Device. (Figure 1 and 2)
2. 2 Logitech C960x HD Pro Webcam Camera. (Figure 3 and 4)
3. NIOSH N95 Masks. (Figure 5 and 6)
4. ANZI Z87 Safety Glasses. (Figure 7 and 8)
5. Safety Vest. (Figure 9)
6. Safety Helmet. (Figure 10)

Figure 1: UP Squared AI Edge Device (front view)

Figure 2: UP Squared AI Edge Device (back view)

https://www.intel.com/content/www/us/en/products/sku/208662/intel-core-i71165g7-processor-12m-cache-up-to-4-70-ghz/specifications.html

Figure 3: Logitech C920x HD Pro Webcam

Figure 4: Logitech C920x HD Pro Webcam with accessory

Figure 5: NIOSH N95 Mask – front view (3M Brand)

Figure 6: NIOSH N95 Mask – Inner view (3M Brand)

Figure 7: ANSI Z87 Safety Glasses

Figure 8: ANSI Z87 Safety Glasses

Figure 9: Safety Vest

Figure 10: Safety Helmet

3.3 Comparing the automated PPE detection technology's ability to detect PPE violations vs video recording reliant on human review in a controlled simulated setting (Phase 3)

After the devices (both automated and video recording systems) has been tested for their scope and limits, we placed alongside the automated PPE detection device, a video recording device (1 Logitech C920 camera and a laptop) with capabilities to capture the same video feed as the automated PPE device captures for 30 seconds per experiment. The camera of the video recording device was placed side by side with the camera of the automated PPE detection device, accounting for camera angle, parallax, positioning, and distance to participants in the study. Both cameras for the automated PPE detection device and the video recording device were the same in terms of type, manufacturer, and resolution. This was to eliminate video recording bias.

The video recording was reviewed by a volunteer reviewer to identify PPE violations during the study. The video reviewing volunteer was trained to identify the specific type of PPE used in this study on specific body parts and immediately record PPE violation(s) on instances they cannot ascertain that a particular object on a specific body part is indeed a type of PPE in use for this study. This review was done within 30 seconds and responses (both number of PPE violations observed and the time (in seconds) it took to make all PPE violation observation) recorded for each experiment.

The automated PPE detection device has an on-screen dashboard, where captured PPE violations data are displayed. Data from the automated PPE detection device was collected for each experiment and recorded as well with a timestamp.

3.3.1 Statistical Analysis

This was an experimental study design, where we compared the ability of the dependent variables (automated PPE detection technology vs CCTV video reviewers) to quickly detect PPE violations against a set of predefined treatment conditions. Examples of treatment conditions that had an effect on the device's ability to detect and report PPE violation during testing include low lighting, high lighting, male and female workers, worker posture, worker positioning, presence of obstacle (clear plexiglass) in view of the camera's line of sight, distance of the worker to the camera, and the view of the worker to the camera (front or side view). We assessed whether or not these factors affect the detection rate and time of both the automated PPE detection device and the video recording device individually and in several combinations. We noted that some of the treatment conditions when combined affected the ability of both devices to correctly detect PPE types or record violations.

The Taguchi orthogonal array method of experiment design was used to randomly select the combination of factors to be assigned to each experiment session. We ran 8 different experiments for 30 seconds each, and the outcome/response data recorded for each experiment was: (1) the number of PPE violations detected, and (2) the time (in seconds) it took to record a violation. This was observed equally for both the automated PPE detection device and the video recording review.

The video recording was done at the same time for each experiment, placing the video recording camera beside the camera of the automated PPE detection device. This video recording was reviewed/rated by a volunteer, and they reported their findings to include the number of PPE violations detected and the time (in seconds) it took to detect whether a violation exists or not. The video reviewer watched the short 30 second video recordings for each experiment only once.

The volunteer was trained in how to recognize the four PPE types used in this study, including distinct PPE features and markings. Where they are unable to accurately ascertain if the test participant has a particular type of PPE on or not (whether PPE violation exists or not), due to the different treatment condition combinations without zooming in the video recording, they are to record it as a violation and record the time (in seconds) it took them to make the conclusion within 30 seconds or at the 30 seconds' mark.

At the end of the review, the video recording review data was compared to the data recorded from the automated PPE detection device and statistical analyses was conducted to determine the significant difference in performance (number of PPE detected and the detection time per experiment) between them.

Chapter 4: Results and Discussion

4.0. Summary.

In this chapter, we analyzed the results of the study. The first part presents an assessment and interpretation of the collected data from the survey questionnaire sent out to participants. It comprises of tables and figures to visually explain the results of the questionnaire. The other part of this chapter presents findings from the lab experiment designed to monitor PPE usage/compliance in a simulated manufacturing setting using actors/volunteers.

4.1.0 Qualtrics Survey Data Analysis

The result from the survey titled "Manufacturing Worker's PPE Compliance Survey *(From a Safety Personnel/Supervisor's Perspective)*" was analyzed in this section using python . All statistical tests were calculated at $\alpha = 0.05$ where applicable. The results analyzed in this section comprised of data collected from the 31 respondents who completed the survey with a 100% completion rate.

Survey link: https://acrobat.adobe.com/link/review?uri=urn:aaid:scds:US:07de2678-d550-3a08-bbb6-0e1bb769899b

4.1.1 Participant's Job Title

Thirty-one (31) of the respondents who completed the survey chose job titles that best fit their roles at their various manufacturing companies. Based on industry practice and expert opinion, we highlighted job titles of safety professionals whose primary role directly involves being responsible for the safety and health of workers under their supervision. From the barchart, 38.7% of the total respondents were safety managers, followed by 25% who selected "others" since their actual job titles were not listed on the survey. These respondents, however, affirmed that they were primarily responsible for the health and safety of the workers under their supervision. About 9.7% of the respondents were either safety officers or safety supervisors, while 6.5% were safety directors and 3.2% were either safety and health officers, floor managers and safety representatives.

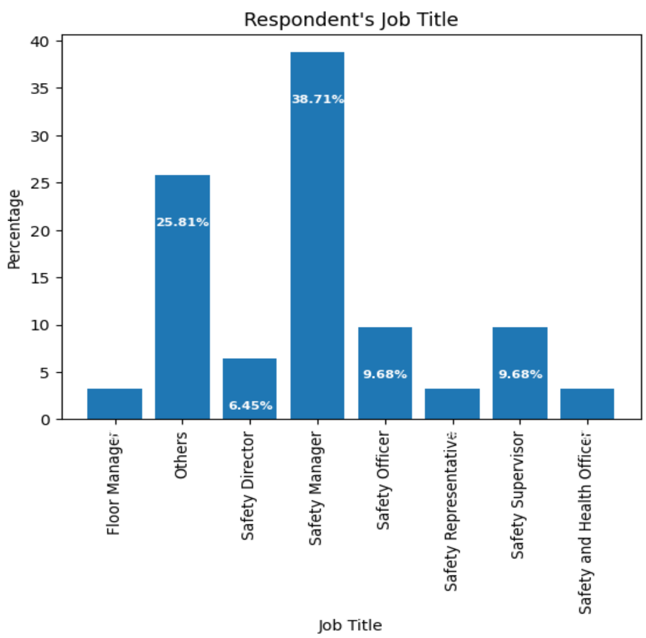

Figure 11: Participant's Job Title

4.1.2 Participant's Years of Experience

From the table below, 32.3% of the respondents have more than 10 years of work experience in a safety and health role, while the rest of the 67.7% have less than 10 years of experience in a safety and health related role. The weighted mean years of work experience for all respondents is 8.3 years as shown below.

Yrs. of Exp.	No. of Resp. (F_i)	Mid Point (X_i)	F_iX_i
0 - 4	11	2	22
5 - 9	10	7	70
10 - 14	6	12	72
15 - 19	2	17	34
20 - 24	0	22	0
25 - 29	1	27	27
30 - 34	1	32	32
35 - 39	0	37	0
40 - 44	0	42	0
45 - 49	0	47	0
50 - 54	0	52	0
	$\sum F_i = 31$		$\sum F_iX_i = 257$

$$\sum \frac{(F_iX_i)}{F_i} = \frac{257}{31} = 8.29$$

Table 1: Participant's years of experience (weighted mean)

Figure 12 below shows the percentage distribution of the years of experience of all the respondents.

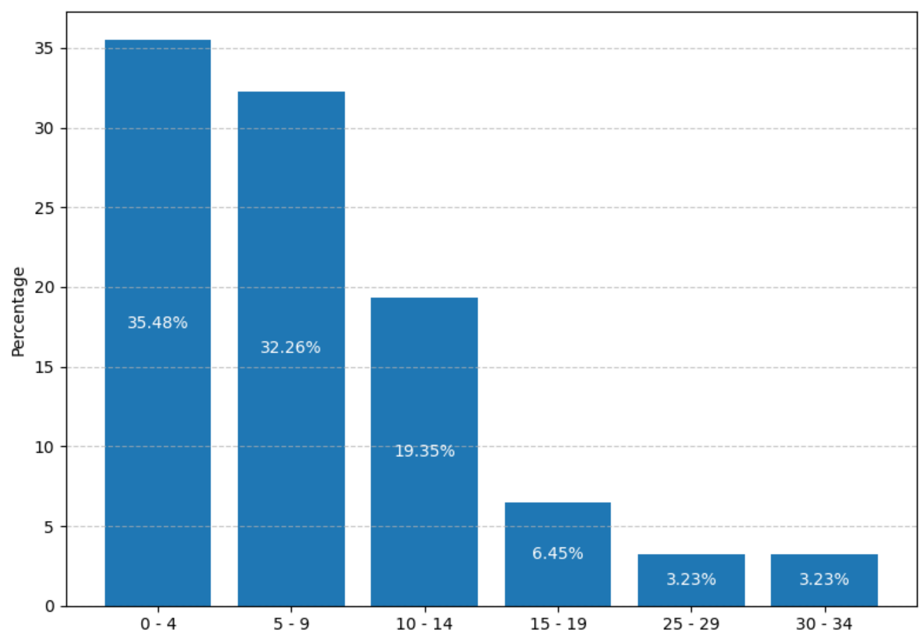

Figure 12: Participant's years of experience

4.1.3 Age, gender and total number of manufacturing workers supervised by survey respondents.

The results showed that the youngest worker in their facility was aged 18 years, while the oldest worker under their supervision was 75 years old. The total number of employees/workers supervised by the respondents was 8453 workers. Of these workers, approximately 79% were male while 21% were female.

4.1.4 Common PPE Used in the Survey Respondent's Plants.

We asked survey respondents to choose the PPE used at their plants among the four (4) commonly used OSHA compliant PPE in the manufacturing industry (selected for this survey). According to their responses, the most frequently used PPE by all respondent's manufacturing plant workers was the safety glasses, accounting for 100% use. This was followed closely by the hearing protection which was used by 97% of respondent's workers. Approximately, 90% of the surveyed respondent's workers used safety glasses and the same percentage used respiratory protection.

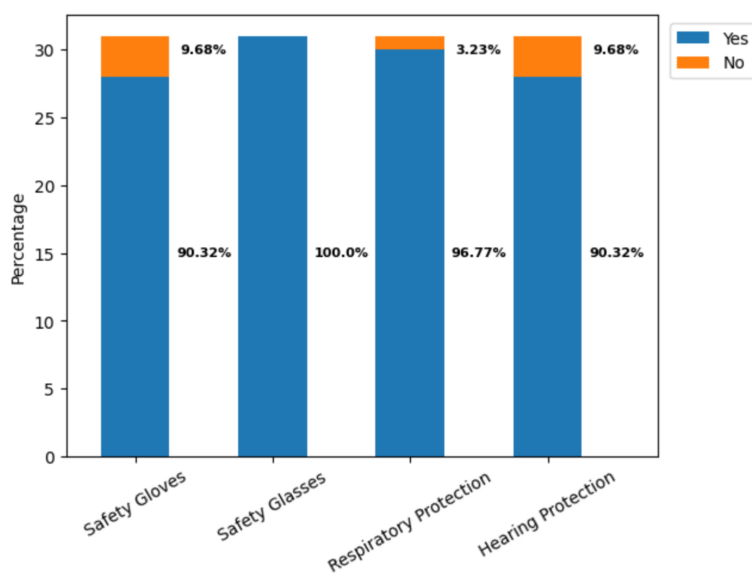

Figure 13: Commonly Used PPE

4.1.5 Most PPE Violation Recorded.

Feedback regarding PPE usage at their facility over the last 6 months, safety glasses were reported as the most commonly violated type, comprising 35 % of the total violations. Hearing protection accounted for approximately 25%, safety gloves for 16%, and respiratory protection for 13% of the total violations. Additionally, 9.7% of the respondents do not know which PPE was most violated at their plant.

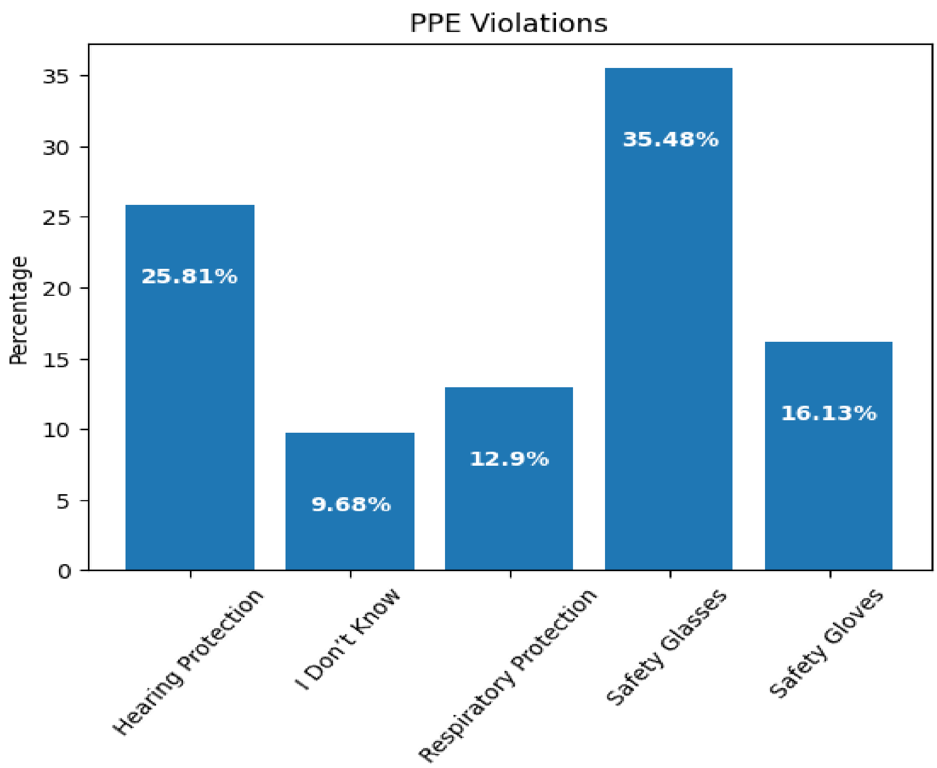

Figure 14: Most Frequently Violated PPE

4.1.6 Days of the Week with the Most PPE Violations.

Respondent's data showed that more than half (54.8%) do not know what day of the week recorded the most PPE violations in the last 6 months. This might be due to the lack of appropriate reporting and recording of PPE violations in their plants. However, from the respondents that have PPE violation records, Fridays was the day that records the most PPE violations among days of the week according to 22.5% of the respondents. Thursdays ranked second just above Saturdays, while Tuesdays and Wednesdays recorded the least PPE violations.

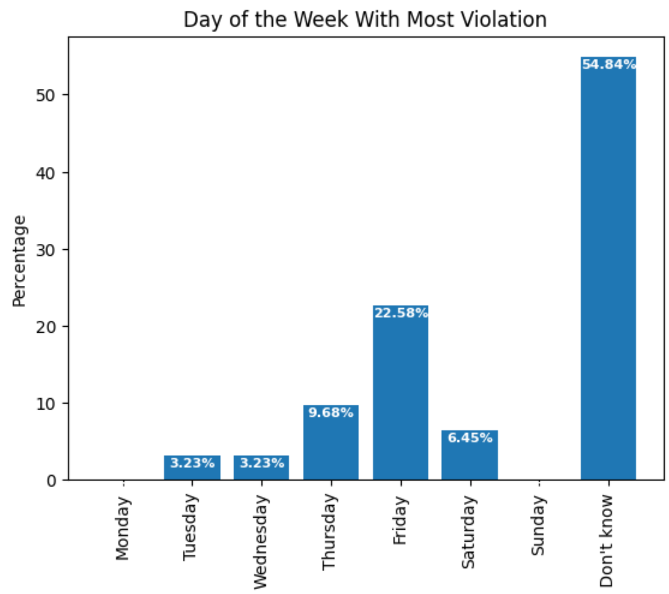

Figure 15: Days with the most PPE Violations

4.1.7 Period of Day with the Most PPE Violations.

We assigned selected time of day to suit the typical period/time of day/work for a regular 8-hour work shift regardless of the starting time to include, beginning of shift, before meal break, after meal break, middle of shift, end of shift, outside of regular shift, and none of the above. The data shows that PPE violations occur mostly in the middle of the shift according to 32% of respondents. 13% of the respondents affirmed that PPE violations occurred the most after meal breaks, 6.5% affirmed that PPE violations occurred mostly at the end of shifts, while 3.2% of the respondents believe that PPE violations occurred before meal breaks and beginning of shifts respectively. About 22.6 % of the respondents affirmed that PPE violations occurred the most outside their shift, while 19.4% selected none of the above period of day.

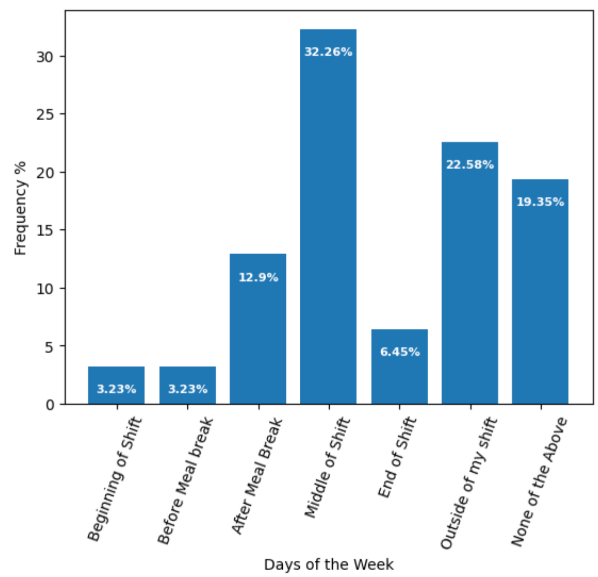

Figure 16: Period of day with the most PPE violations

4.1.8 PPE Compliance Policy.

OSHA act 29 CFR 1910.132(a) – (f) (Personal Protective Equipment – PPE) states the general requirement for PPE compliance. From the survey, we asked respondents specific questions relating to their company's PPE compliance policies in the last six months. The responses to these questions are either "Yes, Always", "Yes Sometimes", "No Never", or I Don't Know". We classified the "Yes, Always" and "Yes Sometimes" responses as "YES".

From the data, 100% of the respondents answered YES to the following questions "I believe our workers are provided with the correct type of PPE?, "Are workers/employees required to wear PPE at all times during work hours?", "Are PPE worn by workers/employees appropriate for protection against the intended hazard they are designed for?", "Do workers correctly wear PPE during work according to company PPE training and/or policy?", "Are PPE (when worn by workers/employees) correctly fitted according to company PPE training and/or policy?", "When worn properly and appropriately, I believe PPE provides protection against injuries preventable by PPE".

Approximately 97% of the respondents answered YES to the question "Do workers/employees occasionally forget to use/wear their PPE while working?", while 3% of them selected "No, Never". About 90% of respondents have seen workers occasionally remove their PPE during work, while 10% have never seen their workers remove their PPE during work. 6.5% of respondents have not noticed an inappropriate use of PPE by workers at their plant in the past six months, meanwhile, 93.5% of them have witnessed inappropriate use of PPE by workers in the same period of time.

PPE Training

As an OSHA requirement, employers are required to train each employee who is required to use PPE. Each employee shall be trained to know at least when PPE use is necessary, what PPE is necessary, how to properly don, doff, adjust, and wear PPE, limitations of the PPE, and the proper care, maintenance, lifespan, and disposal of PPE. In line with this OSHA standard, we asked respondents of the survey what proportion of their workforce has had any form of PPE training (first time training or refresher training) in the last 6 months. From the data, 67.7% of the respondents said 75% - 100% of their workforce have had one form of PPE training, 22.6% said 50% - 75% of their workforce have had one form of PPE training, 6.5% of respondents said 25% - 49% of their workforce have had one form of PPE training, while 3.2% reported that 1% - 24% of their workforce have had PPE training.

PPE Trained Employees (%)	Number of Respondents	(%)
< 1%	0	0
1% - 24%	1	3.3%
25% - 49%	2	6.5%
50% - 74%	7	22.6%
75% - 100%	21	67.7%

Table 1: PPE Training in the last 6 months

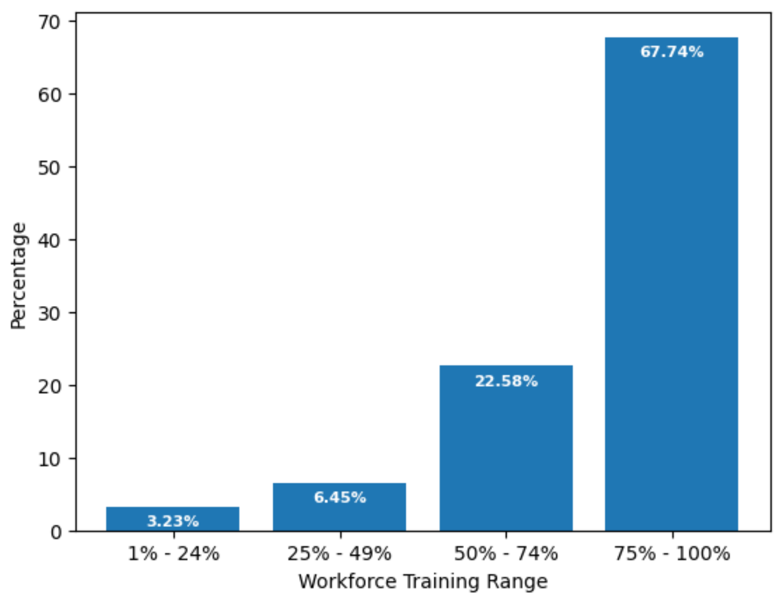

Figure 17: PPE Training in the last 6 months

PPE Training and Number of PPE related injuries

From the data analysis, it was observed that there was no significant association between PPE training and the number of PPE related injuries reported by the respondents. We statistically analyzed the responses between the proportion of PPE trained workers with regards to the total number of PPE related injuries from the survey using the fisher's exact test. The result showed a *p-value* of 0.24 (at $\alpha = 0.05$). Hence, we fail to reject the null hypothesis 1. This shows there is no significant association between PPE training and the number of PPE related injuries.

4.1.9 PPE Violations Related Injuries (First-Aid Injuries)

Based on survey responses, we analyzed the overall PPE violations that resulted in first-aid injuries only (reported from the last 6 months at their plants). The findings are presented in the table and bar chat below.

PPE Related First-Aid Injuries (%)	Number of Respondents	(%)
< 1%	0	0.0%
1% - 24%	18	58.1%
25% - 49%	6	19.4%
50% - 74%	5	16.1%
75% - 100%	0	0.0%
I Don't Know	2	6.5%

Table 2: PPE Related Injuries (First Aid) in the last 6 months

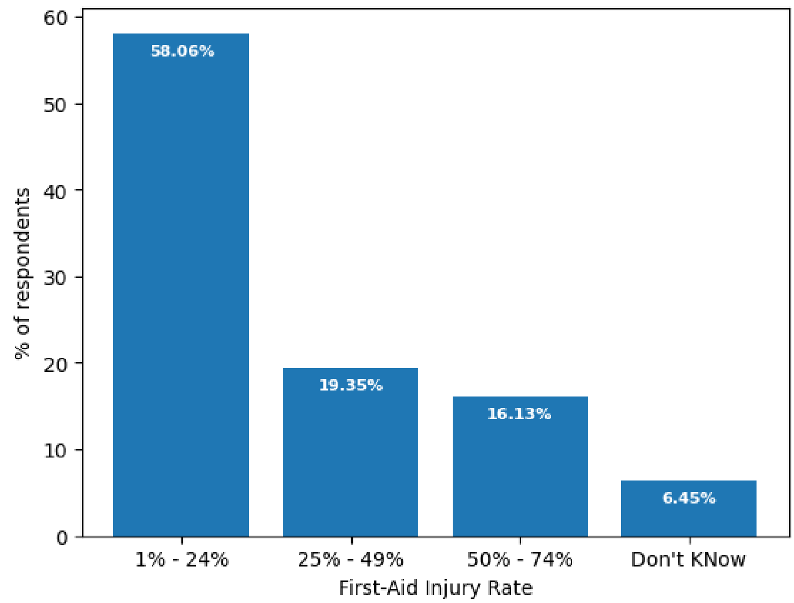

Figure 18: PPE Violations Resulting in First-Aid Injuries

4.1.10 PPE Violations Related Injuries (Beyond First-Aid Injuries)

We also analyzed the overall PPE violations that resulted in injuries beyond first aid as reported by the respondents from the last 6 months at their plants.

PPE Related Beyond First-Aid Injuries (%)	Number of Respondents	(%)
< 1%	7	22.6%
1% - 24%	19	61.3%
25% - 49%	2	6.5%
50% - 74%	0	0.00%
75% - 100%	1	3.2%
I Don't Know	2	6.5%

Table 3: PPE Violations Resulting in Injuries Beyond First Aid

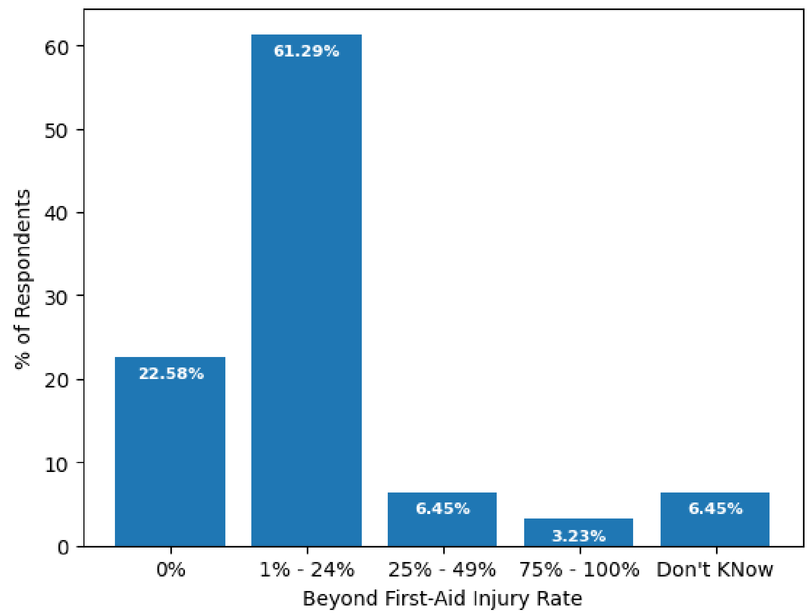

Figure 19: PPE Violations Resulting in Injuries Beyond First Aid

4.1.11 PPE Violations Based on Age of Workers.

We asked respondents to provide information about the trend of PPE violation among their workers based on their age ranges (less than 25 years, 25 to 49 years, and 50 years and above) .

Among workers below the age of 25 years according to 53.3% of the respondents, they had less than 24% of PPE violations including "no violations", while 30% of the respondents reported that they had between 25% - 49% PPE violations, and 16.7% of respondents said that 50% - 74% of their workers recorded PPE violations.

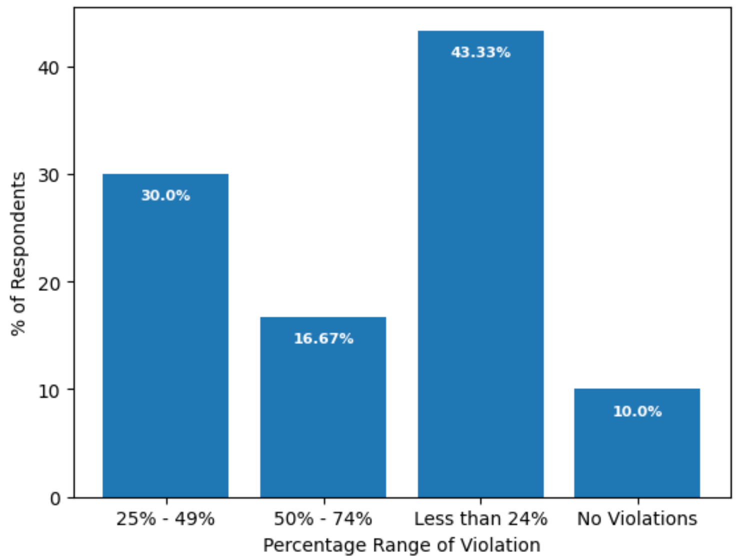

Figure 20: PPE violations Among Workers Aged Less than 25 years.

Among workers aged between 25 years and 49 years, 46.7% of the respondents observed less than 24% PPE violations. 36.7% of the respondents reported 25% - 49% PPE violations among the age group, while 13.3% of respondents said that 50% - 74% of their workers recorded PPE violations. The remaining 3.3% of the respondents reported no PPE violation among this age group according to their records in the last 6 months.

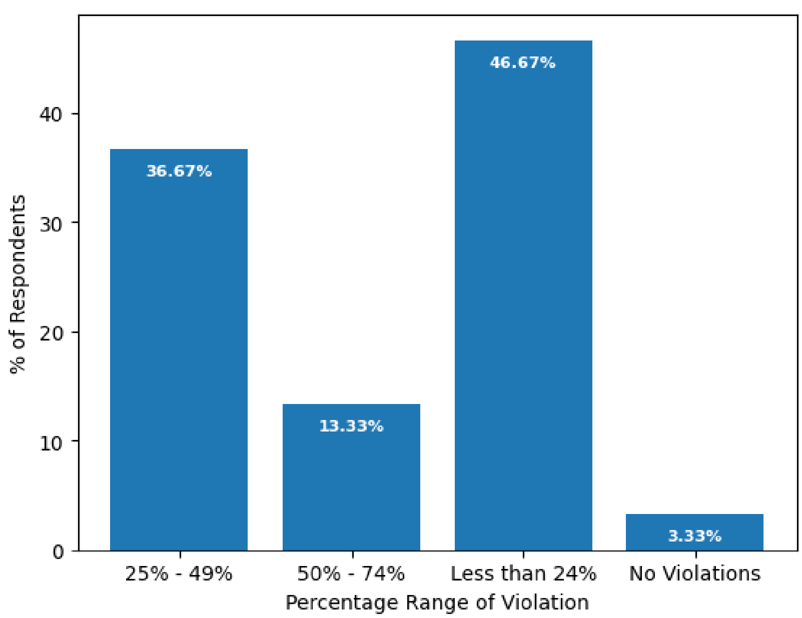

Figure 21: PPE violations Among Workers Aged 25 years to 49 years.

The third age group are the workers aged 50 and above. Seventy percent of the respondents reported less than 24% PPE violations (including “No Violations”) in the last 6 months. Among the rest of the respondents, 20% said they observed 25% - 49% PPE violations and the remaining 10% of the respondents observed 50% - 74% PPE violations among workers who are 50 years old and older.

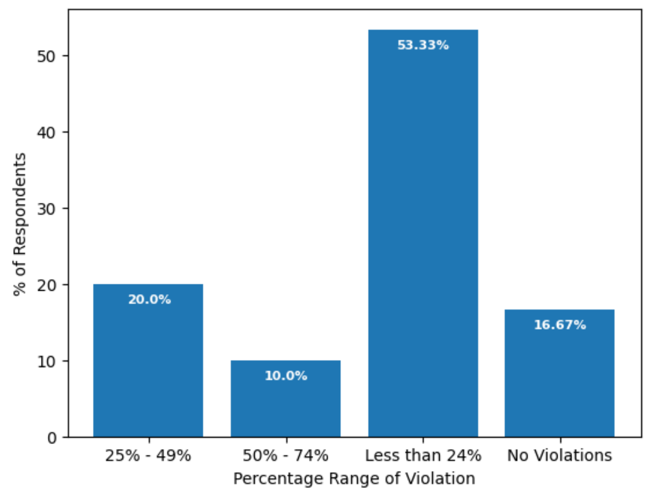

Figure 22: PPE violations Among Workers Aged Less than 25 years.

From the data above, we can infer that PPE violations among middle-aged and younger workers follow a common trend of evenly distributed PPE violations, while PPE violation distribution among workers above the age of 50 slightly differ . We observed that 50% of the middle-aged and younger workers (less than 25 years) recorded lower PPE violations (less than 24%), while the other half recorded more than 25% PPE violations. However, for workers above 50 years of age, 70% of them recorded less than 25% PPE violations while only 10% recorded more than 50% PPE violations. This could suggest that older workers have lower tendencies to violate PPE than younger workers.

4.1.12 Consequences for PPE Violations.

PPE violation consequences could include progressive discipline, suspension or time-off without pay, HR warning letters etc. In safety and health, these are considered as lagging indicators that can be used to influence certain behaviors. In the survey, we asked the respondents about having consequences of PPE violations established at their workplace. 65.5% of the respondents said "Yes, Sometimes", 22.6% of the respondents said "Yes, Always", while only 12.9% answered "No, Never" as they do not have punitive actions against PPE violators.

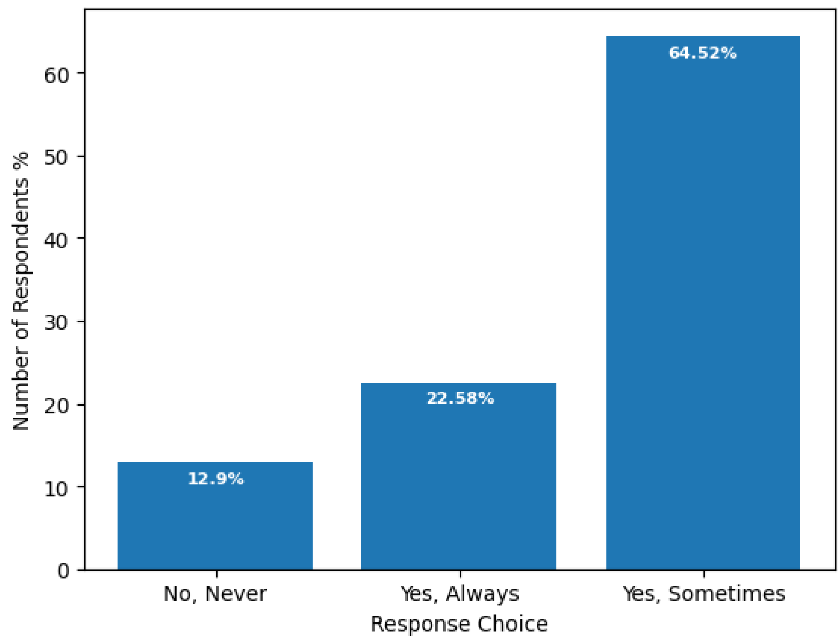

Figure 23: Consequences for PPE violations

We statistically analyzed the responses between the proportion of workplace that have consequences ("Yes sometimes" and "Yes Always) for PPE violations with regards to the total number of PPE related injuries from the survey using the fisher's exact test. The result showed a *p-value* of 0.36 (at $\alpha = 0.05$). Hence, we fail to reject the null hypothesis 1. This shows there is no significant association between consequences for PPE violations and the number of PPE related injuries.

4.1.13 PPE Violation Detection.

When asked if respondents believed they missed PPE violations at their plant in the last 6 months, 85.2% answered “Yes”, they missed PPE violations, while 14.8% of respondents answered “No”, they did not miss any PPE violations. Missed PPE violations detection among workers increases the likelihood of workers getting injured on the job for PPE preventable injuries.

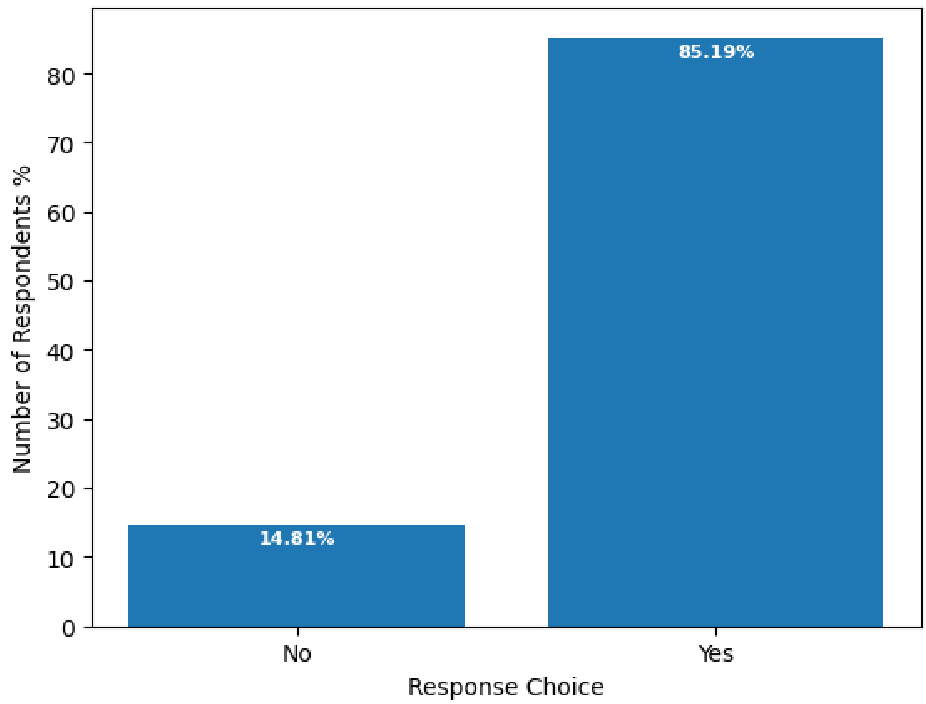

Figure 24: Missed PPE violation.

4.1.14 Proportion of Missed PPE Violations.

The lower the number of missed PPE violations among workers, the lower the likelihood of the workers getting injured for PPE preventable injuries. In the question about what percentage of PPE violations did the respondents believe they missed, only 23 respondents selected an answer choice. The remaining 8 respondents did not pick an answer choice. From the respondents who answered the question, 30% of them believed they missed between 10% - 19% violations and 30% of respondents missed between 20% - 50% of PPE violations. Less than 5% of PPE violations were missed by 17.4% of the respondents, while 8.7% of the respondents missed more than 50% PPE violations in the past 6 months.

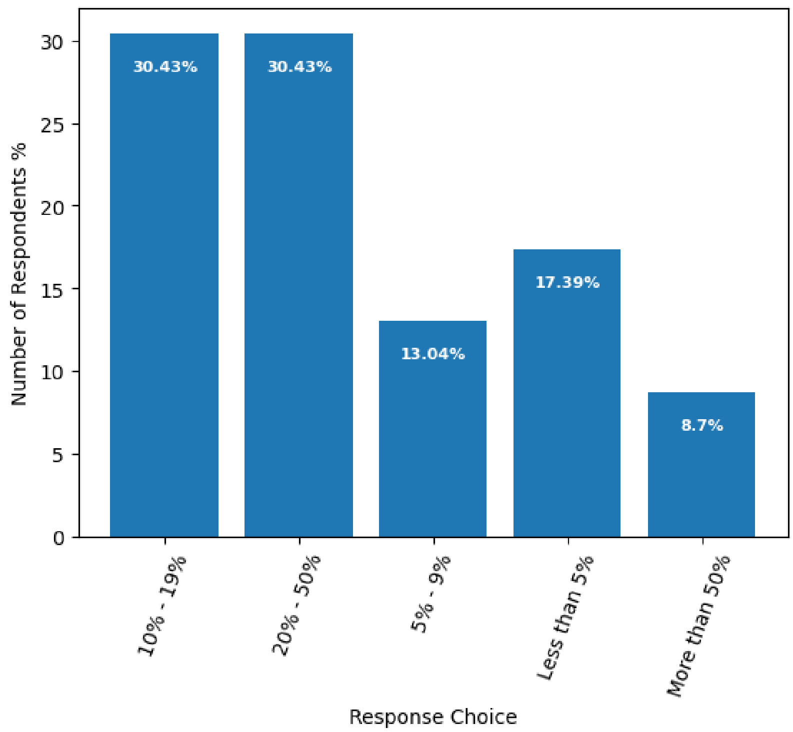

Figure 25: Percentage of missed PPE violations

4.1.15 Assigned PPE Monitoring Personnel.

The most used current trend in PPE compliance monitoring involves using assigned personnel to visually inspect the use of PPE among workers in workplaces where they have PPE programs in place. From the survey response to the question "do you currently have assigned personnel monitoring for PPE compliance at your plant?", 56.7% of respondents said they do not have an assigned person to monitor PPE use among workers, while 43.3% said they have an assigned monitor for PPE compliance.

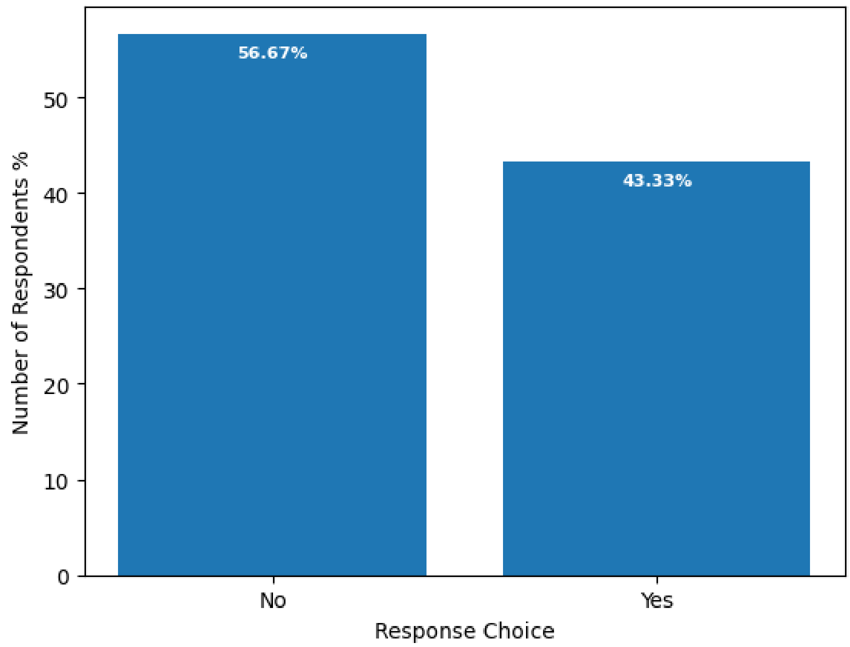

Figure 26: Assigned PPE monitoring personnel.

To assess the effectiveness of assigning PPE monitoring personnel to detect PPE non-compliance in the workplace, respondents were asked if they believe (in their estimation) that safety personnel alone can detect most of the PPE violations in their workplace through visual inspection. 86.7% of the respondents answered “false” to the question. This means that a very large percentage of respondents believed that it is almost impossible for safety personnel alone to accurately detect PPE violation in the workplace. 6.7% of the respondents believe it is possible (“true) for safety personnel to detect most of the PPE violations in the workplace by themselves.

The rest of the respondents were unsure whether safety personnel can or cannot detect most workplace PPE violations by themselves.

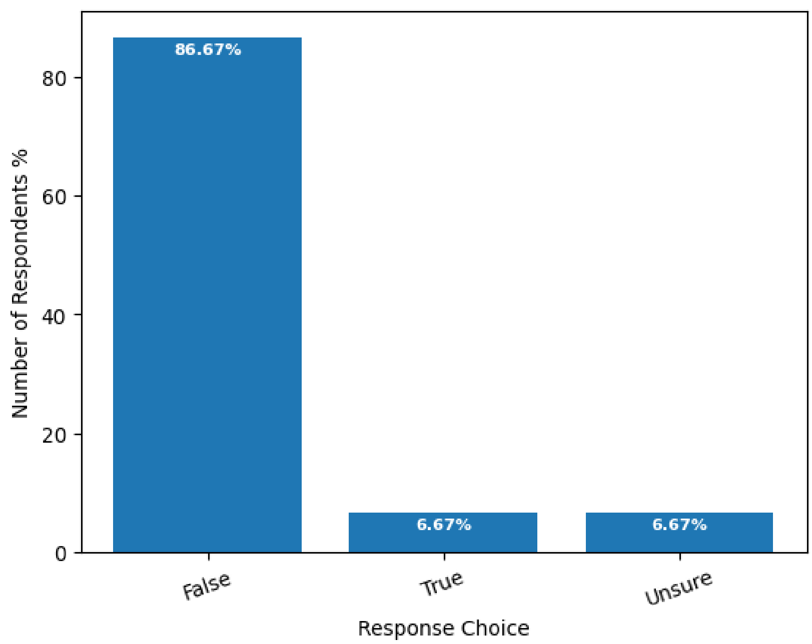

Figure 27: PPE monitoring by safety personnel alone

4.1.16 PPE Monitoring Device.

Respondents were asked if they had any kind of monitoring/video recording device used in monitoring for PPE compliance at their workplace including automated PPE detection device. 48.4% reported that they did not have any kind of PPE monitoring device on site, whereas 29% reported that they relied on the use of security cameras (in real-time) and 22.6% relied on CCTV recording devices to monitor for PPE compliance. None of the respondents had any kind of automated PPE detection device at their plant.

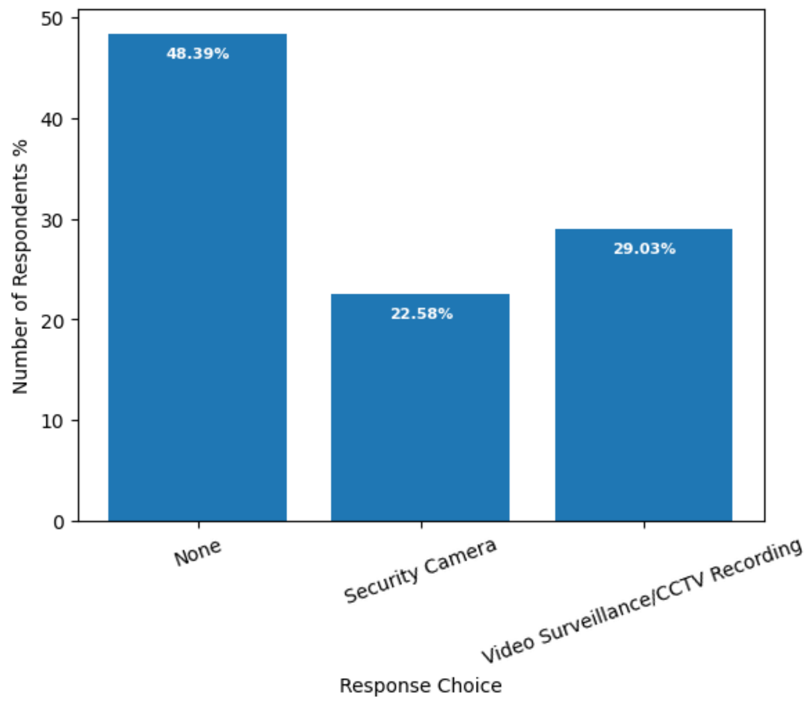

Figure 28: PPE monitoring device

4.1.17 Automated PPE Detection Device and Safety Personnel.

When asked if an automated PPE detection device/system could help increase the detection rate of PPE violations at their workplace, 80.6% of the respondents said they believe that safety personnel with the aid of an automated PPE detection system, can increase the detection of PPE violations in real-time at their plant, , while 3.2% believed the opposite. 16.1% were unsure of the effect of using an automated PPE detection technology in conjunction with safety personnel to increase PPE detection at their workplace.

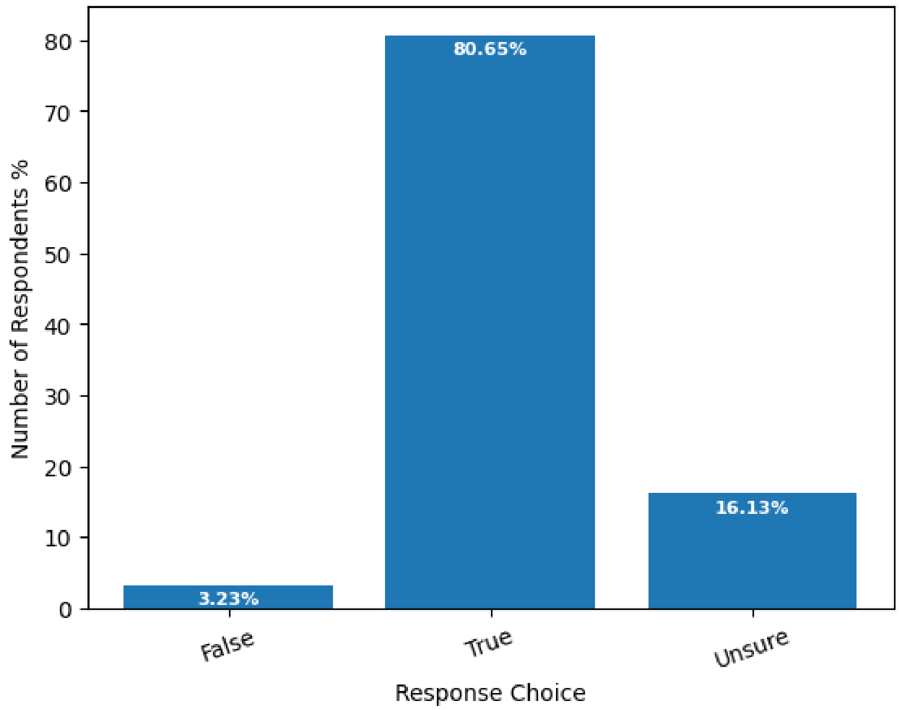

Figure 291: Automated PPE detection device

4.1.18 Summary of Results

The analysis reveals a notable lack of adoption of automated PPE monitoring systems in manufacturing. A significant 85% of survey participants acknowledged the likelihood of missing PPE violations, with a contrasting 15% confident in their thoroughness. Furthermore, more than half of the respondents, 56%, reported not having dedicated staff for PPE monitoring, highlighting a critical gap in supervisory oversight for PPE compliance. Conversely, 43% have appointed monitors. Regarding equipment, 48% of those surveyed lack any PPE monitoring technology, 29% use video or CCTV recordings, and about 23% depend on security cameras, none of which offer consistent, real-time monitoring.

The traditional approach of physical inspection by safety personnel is viewed skeptically, with 86% of respondents doubting its effectiveness in catching most PPE violations. In contrast, over 80% believe that the implementation of automated PPE detection technology could substantially improve the rate and timeliness of violation detection.

This suggests an urgent need to assess the effectiveness and differences between automated PPE detection and video monitoring systems for real-time PPE compliance in the manufacturing sector.

4.2.0 Automated PPE Detection Device Testing

Using the Taguchi Orthogonal Array method of study design, we created an array of treatment factor combinations for each of 8 different experiments. Based on the 7 factors selected during the pilot study, we used the Taguchi Orthogonal L_8 (2^7) Orthogonal Array design of experiment method. 7 factors (level 1 and level 2) were combined for each experiment. In the first experiment, we tested all level 1 factors as stated on the Taguchi orthogonal array table while the worker was positioned at the simulation work zone. The rest of the experiment follows the same process with the factor combinations set for the remainder of the experiments. The whole experiment was repeated 3 times and responses recorded. Table 4 and 5 below show the Taguchi Orthogonal L_8 (2^7) Orthogonal Array table used in this study as well as the treatment conditions (level 1 and 2).

TAGUCHI L_8 (2^7) Orthogonal Array

Exp. Num.	X1 C1	X2 C2	X3 C3	X4 C4	X5 C5	X6 C6	X7 C7
1	1	1	1	1	1	1	1
2	1	1	1	2	2	2	2
3	1	2	2	1	1	2	2
4	1	2	2	2	2	1	1
5	2	1	2	1	2	1	2
6	2	1	2	2	1	2	1
7	2	2	1	1	2	2	1
8	2	2	1	2	1	1	2

Table 4: Taguchi Orthogonal Array

TAGUCHI L_8 (2^7) Experiment Conditions

Exp. Num.	X1 C1	X2 C2	X3 C3	X4 C4	X5 C5	X6 C6	X7 C7
1	**1.** High Lighting	**1.** 6 ft	**1.** Upright Posture	**1.** Front View	**1.** Standing	**1.** Male	**1.** Obstacle
2	**1.** High Lighting	**1.** 6 ft	**1.** Upright Posture	**2.** Side View	**2.** Sitting	**2.** Female	**2.** No Obstacle
3	**1.** High Lighting	**2.** 12 ft	**2.** Bending Posture	**1.** Front View	**1.** Standing	**2.** Female	**2.** No Obstacle
4	**1.** High Lighting	**2.** 12 ft	**2.** Bending Posture	**2.** Side View	**2.** Sitting	**1.** Male	**1.** Obstacle
5	**2.** Low Lighting	**1.** 6 ft	**2.** Bending Posture	**1.** Front View	**2.** Sitting	**1.** Male	**2.** No Obstacle
6	**2.** Low Lighting	**1.** 6 ft	**2.** Bending Posture	**2.** Side View	**1.** Standing	**2.** Female	**1.** Obstacle
7	**2.** Low Lighting	**2.** 12 ft	**1.** Upright Posture	**1.** Front View	**2.** Sitting	**2.** Female	**1.** Obstacle
8	**2.** Low Lighting	**2.** 12 ft	**1.** Upright Posture	**2.** Side View	**1.** Standing	**1.** Male	**2.** No Obstacle

Table 5: List of Factors/Treatment Conditions

Study participants (1 male and 1 female) were asked to wear all the selected 4 PPE (Safety Glasses, Helmet, safety vest and N95 Masks) being evaluated and perform the same task under 7 different conditions with 2 levels each; posture (upright and bending), position (standing and sitting), lighting (low lighting and high lightning), camera view (front view and side view), distance to camera (6 feet and 12 feet), and the presence or absence of an obstacle (plexiglass). Study participants simulated the same task on the 3 ft table using a computer-numerical control (CNC) milling machine for each of the experiments.

When the study participant enters the work zone wearing all required PPE under each experiment conditions, we used a stopwatch device to set a 30 second experiment time. At the 30 second mark, video recording will stop. Another stopwatch device was used to determine the time it took the automated PPE detection device to display the count of violation within the 30 seconds experiment time. Immediately the automated PPE device records the number of violations detected, we recorded the responses (number of violations and the time in seconds it took to detect the violations) . This was repeated 3 times for each of the 8 experiments.

The video recording was also taken at the same time as explained in chapter 3 for the same 30 seconds experiment time for each of the 8 experiments. This was repeated 3 times and responses recorded after review.

4.2.1 Experiment Responses – Automated PPE Detection Device and Video Recording Review

The tables labelled below show the responses of the experiment for each of the devices used for the 8 experiments done.

Exp.	X1	X2	X3	X4	X5	X6	X7	Response 1		Response 2		Response 3	
Num.	C1	C2	C3	C4	C5	C6	C7	No. of PPE Violations	Detection Time (secs.)	No. of PPE Violations	Detection Time (secs.)	No. of PPE Violations	Detection Time (secs.)
1	1	1	1	1	1	1	1	0	4	0	3	0	3
2	1	1	1	2	2	2	2	0	4	0	4	1	3
3	1	2	2	1	1	2	2	1	6	1	4	1	8
4	1	2	2	2	2	1	1	2	8	2	5	2	9
5	2	1	2	1	2	1	2	1	7	1	7	2	7
6	2	1	2	2	1	2	1	1	8	2	8	1	5
7	2	2	1	1	2	2	1	2	9	2	9	2	9
8	2	2	1	2	1	1	2	1	10	1	9	1	11

Table 6: Taguchi responses for automated PPE detection device.

Exp.	X1	X2	X3	X4	X5	X6	X7	Response 1		Response 2		Response 3	
Num.	C1	C2	C3	C4	C5	C6	C7	No. of PPE Violations	Detection Time (secs.)	No. of PPE Violations	Detection Time (secs.)	No. of PPE Violations	Detection Time (secs.)
1	1	1	1	1	1	1	1	0	7	0	6	0	5
2	1	1	1	2	2	2	2	0	9	0	9	1	6
3	1	2	2	1	1	2	2	1	12	1	10	2	12
4	1	2	2	2	2	1	1	2	10	2	13	2	15
5	2	1	2	1	2	1	2	1	7	2	9	2	8
6	2	1	2	2	1	2	1	1	10	1	10	1	12
7	2	2	1	1	2	2	1	2	15	2	17	1	18
8	2	2	1	2	1	1	2	3	22	2	20	2	17

Table 7: Taguchi experiment responses for video recording review.

4.2.2 Analysis of Test Responses – Automated PPE Detection Device and Video Recording Review

From the result above, we computed the average responses for the number of PPE violations detected and the detection time (in seconds) for both devices use. The result was then used in the statistical analysis of the data. From the result we computed t-tests : two-sample assuming unequal variance for the number of PPE violation detected by the automated PPE detection device and the video recording review. Similar t-test results were generated for the detection time (in seconds) it took both the automated PPE detection device and the video recording reviewer to detect and record a violation. The table below shows a summary of the results. All other statistical outputs can be found in the appendix section below.

Responses	Mean		Standard Error	p-value
	Automated System	Video Review		
PPE Violations Detected	1.13	1.29	0.50	0.33
Detection Time (Sec.)	6.67	11.63	1.11	0.02

Table 8: Experiment Statistical Result Table

4.3 Summary of Results

The analysis of the survey data revealed that all statistical tests yielded p-values greater than 0.05 (at a significance level of $\alpha = 0.05$). Consequently, we fail to reject Null Hypothesis 1, which posits that factors such as PPE training, consequences for PPE violations, and the tenure of workers do not significantly influence the incidence of PPE non-compliance-related injuries among manufacturing workers.

The testing of Hypothesis 2, which asserts that manufacturing environments employing automated PPE detection devices do not record fewer PPE violations compared to environments utilizing video recording (with human raters/reviewers), under specific conditions (including lighting, worker posture, position, distance to camera, gender, camera visibility, and presence of obstacles like plexiglass), yielded a p-value of 0.33 (at $\alpha = 0.05$) using a one-tailed t-test assuming unequal variances. Therefore, we fail to reject this null hypothesis as well, indicating no statistically significant difference in the number of PPE violations detected by automated devices as opposed to human reviewers.

However, the results indicate that automated PPE detection devices identify and log PPE violations more swiftly than video recording reviews. With a p-value of 0.02 (refer to Table 8) at $\alpha = 0.05$, using a two-tailed t-test assuming unequal variances, this finding addresses and refutes the third hypothesis, which posited no significant difference in detection times between automated PPE detection devices and human video reviewers under various treatment conditions. This outcome leads us to reject the null hypothesis, demonstrating a significant difference in detection and recording speed of PPE violations in a manufacturing laboratory setting by the automated device compared to the video recording review.

Chapter 5: Conclusion

5.0 Introduction

This chapter discusses the results of the findings from this study, elaborates on the limitations of the study as well as recommend future directions for further investigation or research.

The survey results indicate that a significant majority of respondents (70%) either do not employ video monitoring systems for PPE compliance or rely solely on security camera footage. Conversely, 29% of the participants reported using video surveillance specifically for monitoring PPE compliance. Notably, none of the respondents reported the use of automated PPE detection devices in their facilities.

Regarding perceptions of the potential effectiveness of automated PPE detection/monitoring devices in enhancing the detection of PPE violations, a substantial 80% of respondents affirmed their belief in the efficacy of such technology. Only a small fraction (3%) expressed disagreement, while 16% remained uncertain about its effectiveness.

These findings underscore a growing recognition and potential readiness for adopting automated PPE detection technologies within the manufacturing sector, suggesting a shift away from traditional methods like visual inspections towards more advanced, technology-driven solutions. Automated PPE detection devices are an essential tool in ensuring the safety and well-being of workers in various industries. These devices use advanced technologies, high-tech cameras, sensors, and machine learning algorithms to monitor the use of PPE, consequently preventing accidents and injuries. Among the foremost benefits of these devices is their capacity to deliver live video streams, enabling real-time on-site monitoring and prompt response to any instances of PPE non-compliance. This capability is especially crucial in sectors like construction, manufacturing, and oil and gas, where the risk of accidents is high, and the repercussions can be severe. This real-time intervention potential greatly enhances safety protocols in these industries (Delhi et al., 2020).

Previous PPE detection studies have recommended some forms of PPE detection devices (Barro-Torres et al. 2012: Balakreshnan et al., 2020). The devices use different technologies to monitor PPE usage. Wearable sensors, for example, employ sensors embedded in PPE items or worn by individuals to monitor their usage. Smart hard hats or safety vests can have built-in sensors that detect the presence of other required PPE items when worn. RFID-based systems, on the other hand, use Radio Frequency Identification (RFID) technology to track the presence of PPE items by attaching RFID tags to the equipment. The devices then scan the area and identify whether the required PPE items are within proximity.

Automated PPE detection has several advantages over other methods of monitoring PPE usage. One of the most significant advantages is their ability to provide real-time monitoring of PPE usage. Video-based systems analyze video feeds in real-time, allowing for immediate detection of any violations or non-compliance with PPE requirements. This enables prompt intervention or corrective actions to ensure the safety of workers. Another advantage of video-based systems is their ability to cover a wide area or multiple workstations simultaneously. By utilizing cameras strategically placed in key locations, they can monitor a larger area or multiple points of interest simultaneously.

The automated PPE detection device used in this study is able to detect PPE violations on multiple individuals at the same time and in real-time and record the sum of the violations on screen for use by the end users.

Reliance on video recording reviews to detect PPE compliance incidents is exhausting, time consuming and expensive, especially in workplaces with a large number of employees working at the same time. The probability of a PPE related injury occurring before the video recording is reviewed for PPE compliance in an industrial setting is significantly higher than the chances of an injury occurring when you employ a video based real-time automated PPE monitoring device. With an automated PPE detection system, a user can immediately, in real-time ensure timely corrective actions to PPE violators and mitigate PPE related injuries.

Video-based systems are also flexible and scalable. Additional cameras can be installed or repositioned as needed to monitor specific areas or accommodate changes in the workplace layout. Ultimately, a video-based PPE detection system provides visual evidence of PPE compliance or violations. Recorded video footage can also be used for documentation, analysis, training purposes, or investigation in case of incidents or accidents.

While automated PPE detection devices have many benefits in improving safety compliance in industries, there are also some limitations to their use. One limitation is the potential for false positives or false negatives, which can lead to unnecessary alarms or missed violations. From the study experiment, the automated PPE detection device recorded false alarms of PPE violations because of certain treatment conditions that interfered with its ability to accurately detect the study participant's used PPE, especially when they turned sideways, in low lighting conditions and about 12ft away from the camera feed. Additionally, these devices may not be able to detect certain types of PPE, such as earplugs or respirators, which may require different detection methods (Gao et al., 2021). Furthermore, there may be privacy concerns related to the use of video-based systems, and appropriate protocols should be in place to handle video data in accordance with privacy regulations and organizational policies.

5.1 Limitations, Overall Conclusions, Future Directions/Research

Limitations

There are a few limitations in this study.

1. The small size of the survey sample resulted in non-significant statistical tests at an alpha level of 0.05. Expanding the sample size could alter the significance of factors like training and work experience on PPE compliance in manufacturing. A larger sample is recommended for deeper analysis.
2. The testing of the automated PPE detection device was restricted to a single participant (male or female) per experiment. While capable of detecting multiple participants simultaneously, this feature wasn't explored.
3. The research utilized a demo version of the PPE detection device due to budget constraints, and the testing occurred in a simulated environment. This limits the generalizability of the findings.
4. Limited camera use (one per device) and fixed positioning led to discrepancies in the detection of PPE violations, raising concerns about false positives.
5. The study's use of a limited simulated manufacturing task means its findings should not be overgeneralized to all worker activities in manufacturing settings.

Conclusion

In summary, the data reported in this dissertation addresses the issue of PPE compliance monitoring in a manufacturing environment. The information from the study will inform safety professionals and manufacturing industry experts on the best method of detecting and ensuring PPE compliance in real time in order to reduce associated costs related to PPE preventable injuries.

From the survey, all statistical tests performed showed an output of p-value greater than 0.05 (at $\alpha = 0.05$), hence we fail to reject the null hypothesis 1: variables such as PPE training, consequences for PPE violations and years of experience (tenure) of workers have no significant effect on PPE non-compliance related injuries among manufacturing workers.

Test for the second hypothesis: "Manufacturing environment that uses automated PPE detection devices do not record fewer PPE violations than manufacturing environment that uses video recording (with the aid of raters/reviewers) within a set time frame under certain treatment conditions, such as lighting, worker posture, worker position, distance of worker to camera, male or female workers, view of worker to camera, presence of an obstacle (plexiglass in between the camera and the worker)", resulted in a p-value of 0.33 (at $\alpha = 0.05$) using a one-tailed t-test assuming unequal variances. Hence, we fail to reject the null hypothesis, since there is no evidence of a significant difference in the number of PPE violations detected by the automated PPE detection device when compared to the number of violations detected by the video recording reviewers. Taking a wholistic look at the number of PPE violations detected by both the automated PPE detection device and the video recording review per experiment across the three responses, it is evident that the PPE violations recorded for both PPE monitoring devices were not different.

From the result of the experiments, it could be deduced that the automated PPE detection device detects and records PPE violations faster than the video recording review. With a p-value of 0.02 (table 8) at $\alpha = 0.05$, using a two-tailed t-test assuming unequal variances, this addresses the assumption raised in the third hypothesis: There is no significant difference in the time it takes for an automated PPE detection device to detect PPE violations in real-time and the time it takes a video recording reviewer to detect PPE violations under certain treatment conditions such as lighting, worker posture, worker position, distance of worker to camera, male or female workers, view of worker to camera, presence of an obstacle (plexiglass in between the camera and the worker). Therefore, we reject the null hypothesis. This value proves that there is a significant difference in the time it takes for the automated PPE detection device to detect and record a PPE violation in a manufacturing lab setting when compared to a video recording review.

Feedback from this study infer that the use of automated PPE detection devices in the manufacturing environment offers a timely intervention in detecting and hence addressing PPE compliance issues among manufacturing workers, thereby reducing the risk of injuries and illnesses as well as decrease the associated costs of PPE non-compliance. PPE violations have been listed on the top 10 OSHA violations for the past 5 years consecutively. The recommendations on the adoption and use of automated PPE detection technology could also serve as guidance for automated PPE detection manufacturers, regulatory agencies, and safety professionals when designing, testing, and adopting PPE monitoring systems in the manufacturing industry.

Future Directions/Research

The following future directions should be considered for future research studies.

1. To provide more comprehensive recommendations for the use of automated PPE detection devices in manufacturing settings, it is recommended that future studies be conducted in real manufacturing environments with actual workers. This will allow for the natural body movements of typical manufacturing workers to be considered, which was not considered in this study, as well as real-world manufacturing environmental conditions and factors.
2. Furthermore, it is suggested that additional high-resolution cameras be utilized in future studies to provide a 360-degree view of the worker during testing. In this study, only one camera was used, resulting in false positive PPE violation calls when the worker turned sideways from the camera's view, particularly with safety glasses. This issue can be resolved by using multiple cameras to provide both the automated PPE detection device and the video recording reviewer with a continuous view of the study participants' facial features, resulting in accurate PPE violation calls.

3. It is recommended that future studies use a more robust automated PPE detection device for data collection. The demo version used in this study has certain limitations that can be overcome with a more advanced device.
4. Consideration should also be given to specifically surveying small and medium manufacturing enterprises in order to better understand how the factors assessed in this survey affects both large and smaller manufacturing work environments.

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Appendix

FIGURES

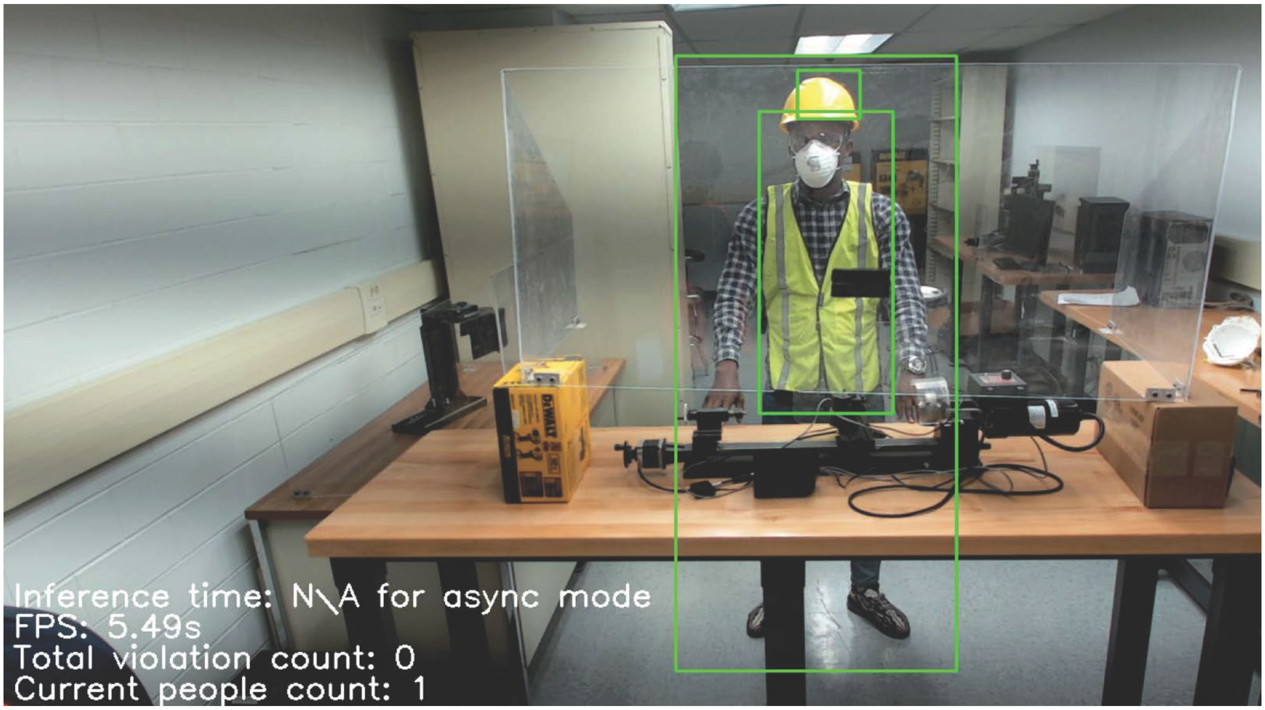

Figure 30: Volunteer during experiment.

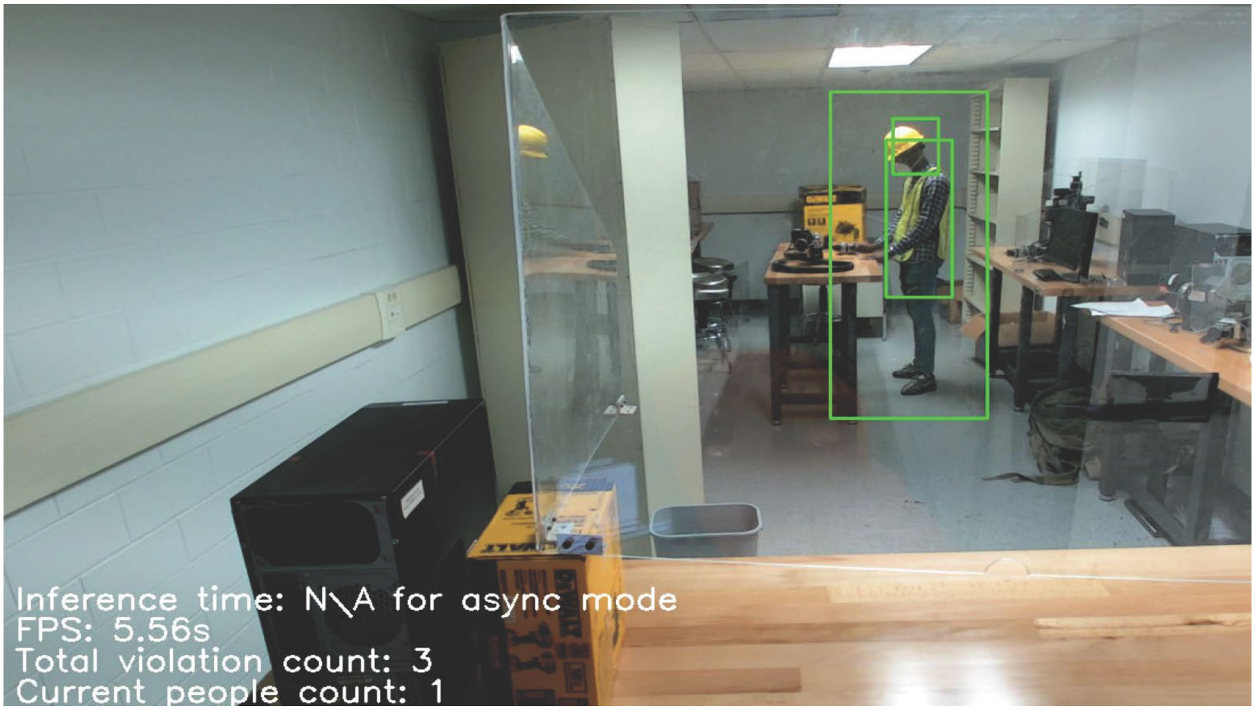

Figure 31: Volunteer during experiment.

4/18/23, 10:28 AM Qualtrics Survey Software

PARTICIPANT CONSENT

Dear Prospective Participant,

This letter is a request for you to participate in a research project which aims to investigate and understand the prevalence of Personal Protective Equipment (PPE) non-compliance in the manufacturing settings. It is a preliminary phase of a much larger project which aims to improve the health and safety of manufacturing workers by detecting and addressing PPE violations in real-time with the use of automated PPE detection technology. This project is being conducted by Joseph Fasinu in the department of Industrial and Management Systems Engineering at West Virginia University (WVU) under the supervision of Dr. Jeremy Gouzd, a teaching assistant professor and the Occupational Safety and Health (PhD) program coordinator in the department of Industrial and Management Systems Engineering, to fulfill requirements for a Doctoral Degree in Research.

If you decide to participate, you will be asked to complete an anonymous Qualtrics survey with multiple choice questions. Your participation in this project will take approximately 15 minutes. You must be 18 years of age or older to participate and the safety and health of workers in your plant must be one of your primary duties.

Your participation in this project will be kept as confidential as legally possible. All responses will be sent directly to the Qualtrics database electronically and only the research team will have access to responses. All data will be reported in the aggregate. You will not be asked any questions that could lead back to your identity as a participant. Your participation is entirely voluntary. You may skip any question that you do not wish to answer, and you may stop participating at any time. Your employment status will not be affected if you decide not to participate or withdraw. The West Virginia University Institutional Review Board's approval of this project is on file with the WVU Office of Human Research Protections.

https://wvu.yul1.qualtrics.com/Q/EditSection/Blocks/Ajax/GetSurveyPrintPreview?ContextSurveyID=SV_4GEKx7PjSbCSXRk&ContextLibraryID=UR_… 1/2

Figure 34: PPE Survey consent form

Survey link: https://acrobat.adobe.com/link/review?uri=urn:aaid:scds:US:07de2678-d550-3a08-bbb6-0e1bb769899b

PARTICIPANT CONSENT

Dear Prospective Participant,

This letter is a request for you to participate in a research project which aims to investigate and understand the prevalence of Personal Protective Equipment (PPE) non-compliance in the manufacturing settings. It is a preliminary phase of a much larger project which aims to improve the health and safety of manufacturing workers by detecting and addressing PPE violations in real-time with the use of automated PPE detection technology. This project is being conducted by Joseph Fasinu in the department of Industrial and Management Systems Engineering at West Virginia University (WVU) under the supervision of Dr. Jeremy Gouzd, a teaching assistant professor and the Occupational Safety and Health (PhD) program coordinator in the department of Industrial and Management Systems Engineering, to fulfill requirements for a Doctoral Degree in Research.

If you decide to participate, you will be asked to perform a simple manufacturin task (millin a piece of aluminum with a rid eport illin achine to show work process flow and how flyin ob ects (pieces of aluminum could affect workers completin this work process his task will be carried out at the ane nnovation ub (dvanced anufacturin lab his is an anonymous video/photo recordin and will only be used solely for this research. here will be no publication of your videos or photos, since it will only be used for illustrative purpose Your participation in this project will take approximately 5 minutes. You must be 18 years of age or older to participate and be an e perienced manufacturin worker

Your participation in this project will be kept as confidential as legally possible. All video and photo records will be stored electronically and only the research team will have access to them All data will be discarded as soon as research is completed to ensure privacy of data. You will not be asked any questions or information that could lead back to your identity as a participant. Your participation is entirely voluntary. Your employment status will not be affected if you decide not to participate or withdraw. The West Virginia University Institutional Review Board's approval of this project is on file with the WVU Office of Human Research Protections.

If you have any questions about this research project, please feel free to contact me at +13042939474 or by email at jeremy.gouzd@mail.wvu.edu. Additionally, you can contact the WVU Office of Human Research Protections at 304-293-7073.

I hope that you will participate in this research project, as it could help us better understand how to protect workers from injuries and illness preventable by the appropriate use of personal protective equipment. Thank you for your time and consideration.

Sincerely,

Dr. Jeremy Gouzd

○ Yes, I Consent To Participate

○ No, I do not Consent To Participate

____

Signature and Date

Figure 34: Study participant consent form

WestVirginiaUniversity.
OFFICE OF HUMAN RESEARCH PROTECTIONS
886 Chestnut Ridge Road Morgantown, WV 26506

Acknowledgement of Not Human Subjects Research

08/02/2022

To: Jeremy Gouzd
From: WVU Office of Human Research Protections

Protocol Type: NHSR / Flex
Submission Type: Initial
Funding: N/A

Approval Date: 08/02/2022
Expiration Date: 08/01/2027

WVU Protocol #: 2208621455
Protocol Title: Personal Protective Equipment (PPE) Dissertation.

The federal definition of research includes the designation for a certain classification of research activities and other projects referred to as "Not Human Subjects Research" or NHSR. This designation allows certain research and research-related projects and activities to be excluded from IRB review and approval.

For example, an activity might qualify for an NHSR designation under federal regulations because:

- The activity does not meet the HHS or FDA federal definition of "research" that requires IRB review, amendments and/or approvals.
- The activity meets the HHS or FDA definition of "research," but does not meet the corresponding regulatory definition of "human subject" requiring IRB review, amendments and/or approvals.

The West Virginia University Institutional Review Board has determined that your submission of protocol 2208621455 qualifies as "Not Human Subject Research" as provided under federal regulations. This determination was based on the following:

- This project has been deemed not human subjects research because as a quality improvement or quality assurance project, it will not contribute to generalizable knowledge and therefore, does not meet the definition of research. Research means a systematic investigation, including research development, testing, and evaluation, designed to develop or contribute to generalizable knowledge.

The following documents were reviewed and acknowledged for use as part of this submission. Only the documents listed below may be used in the research. Please access and print the files in the Notes & Attachments section of your approved protocol.

- Conflict Of Interest - JOSEPH FASINU.pdf
- IRB DATA PROTECTION CERTIFICATE - JOSEPH FASINU.pdf
- JOSEPH FASINU - Form-25 IC OMR Cover Letter.pdf
- PPE DISSERTATION SURVEY - Qualtrics.pdf
- CITI TRAINING CERTIFICATE - JOSEPH FASINU.pdf
- DR. GOUZD - CITI CERTIFICATE.pdf
- JOSEPH FASINU - Form-25 IC OMR Cover Letter.docx

WVU IRB acknowledgement of protocol 2208621455 will expire on 08/01/2027.

Amendments and continuing reviews are not accepted for this type of study. You may continue this study beyond the expiration date if no changes are made to your study that exclude it from NHSR eligibility.

If changes are made to your study that exclude it from NHSR eligibility, it is your responsibility to resubmit it to the IRB as a new, initial submission under the appropriate protocol type.

The WVU Office of Human Research Protections will be glad to provide assistance to you throughout the research process. Please feel free to contact us by phone, at 304.293.7073 or by email at IRB@mail.wvu.edu.

Sincerely,

BS, CCRP

Joseph Malcolm
Program Coordinator

Protocol #: 2208621455 | Phone: 304-293-7073
FWA: 00005078 | Fax: 304-293-3098

Figure 35: IRB Approval

TABLES

L_8 (2^7) Orthogonal Array - Responses for Video Recording Review

Exp.	X1	X2	X3	X4	X5	X6	X7	Response 1		Response 2		Response 3		Average Responses	
Num.	C1	C2	C3	C4	C5	C6	C7	No. of PPE Violations	Detection Time (secs.)	No. of PPE Violations	Detection Time (secs.)	No. of PPE Violations	Detection Time (secs.)	Average PPE Violations	Average Detection Time (secs.)
1	1	1	1	1	1	1	1	0	7	0	6	0	5	0.00	6.00
2	1	1	1	2	2	2	2	0	9	0	9	1	6	0.33	8.00
3	1	2	2	1	1	2	2	1	12	1	10	2	12	1.33	11.33
4	1	2	2	2	2	1	1	2	10	2	13	2	15	2.00	12.67
5	2	1	2	1	2	1	2	1	7	2	9	2	8	1.67	8.00
6	2	1	2	2	1	2	1	1	10	1	10	1	12	1.00	10.67
7	2	2	1	1	2	2	1	2	15	2	17	1	18	1.67	16.67
8	2	2	1	2	1	1	2	3	22	2	20	2	17	2.33	19.67

Table 8

L_8 (2^7) Orthogonal Array - Responses for Automated PPE detection device

Exp.	X1	X2	X3	X4	X5	X6	X7	Response 1		Response 2		Response 3		Avg Response	
Num.	C1	C2	C3	C4	C5	C6	C7	No. of PPE Violations	Detection Time	No. of PPE Violations	Detection Time	No. of PPE Violations	Detection Time	Avg # PPE Violations	Avg Det. Time
1	1	1	1	1	1	1	1	0	4	0	3	0	3	0.00	3.33
2	1	1	1	2	2	2	2	0	4	0	4	1	3	0.33	3.67
3	1	2	2	1	1	2	2	1	6	1	4	1	8	1.00	6.00
4	1	2	2	2	2	1	1	2	8	2	5	2	9	2.00	7.33
5	2	1	2	1	2	1	2	1	7	1	7	2	7	1.33	7.00
6	2	1	2	2	1	2	1	1	8	2	8	1	5	1.33	7.00
7	2	2	1	1	2	2	1	2	9	2	9	2	9	2.00	9.00
8	2	2	1	2	1	1	2	1	10	1	9	1	11	1.00	10.00

Table 9

No. of Experiments	Avg No. PPE Violations (Automated Device)	Avg No. PPE Violations (Video Review)
1	0.00	0.00
2	0.33	0.33
3	1.00	1.33
4	2.00	2.00
5	1.33	1.67
6	1.33	1.00
7	2.00	1.67
8	1.00	2.33

t-Test: Two-Sample Assuming Unequal Variances		
	Variable 1	*Variable 2*
Mean	1.13	1.29
Variance	0.51	0.65
Observations	8.00	8.00
Hypothesized Mea	0.00	
df	14.00	
t Stat	-0.44	
P(T<=t) one-tail	0.33	**Hyp. 2**
t Critical one-tail	1.76	
P(T<=t) two-tail	0.67	
t Critical two-tail	2.14	

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.76
R Square	0.58
Adjusted R Squa	0.50
Standard Error	0.50
Observations	8.00

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	2.04	2.04	8.12	0.03
Residual	6	1.50	0.25		
Total	7	3.54			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	0.26	0.35	0.74	0.49	-0.60	1.12	-0.60	1.12
X Variable 1	0.67	0.23	2.85	0.03	0.09	1.24	0.09	1.24

Table 10: Average number of PPE violations detected – automated PPE detection device vs video recording reviewer.

No. of Experiments	Average Detection Time in Secs. (Automated Device)	Average Detection Time in Secs. (Video Review)
1	3.33	6.00
2	3.67	8.00
3	6.00	11.33
4	7.33	12.67
5	7.00	8.00
6	7.00	10.67
7	9.00	16.67
8	10.00	19.67

t-Test: Two-Sample Assuming Unequal Variances

	Variable 1	*Variable 2*
Mean	6.67	11.63
Variance	5.40	21.44
Observations	8.00	8.00
Hypothesized Mea	0.00	
df	10.00	
t Stat	-2.71	
P(T<=t) one-tail	0.01	
t Critical one-tail	1.81	
P(T<=t) two-tail	0.02	**Hyp. 3**
t Critical two-tail	2.23	

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.90
R Square	0.80
Adjusted R Squar	0.77
Standard Error	1.11
Observations	8.00

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	30.41	30.41	24.75	0.00
Residual	6	7.37	1.23		
Total	7	37.78			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	1.43	1.12	1.28	0.2485	-1.31	4.18	-1.31	4.18
X Variable 1	0.45	0.09	4.97	0.0025	0.23	0.67	0.23	0.67

Table 11: Average PPE violation detection time (in seconds) – automated PPE detection device vs video recording reviewer.