Modeling and Qualification of Future Digitalized Assembly Work

by

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THESIS PRESENTED TO ÉCOLE DE TECHNOLOGIE SUPÉRIEURE
IN PARTIAL FULFILLMENT FOR A MASTER'S DEGREE
WITH THESIS IN OCCUPATIONAL HEALTH AND SAFETY RISK
M.A.Sc.

MONTREAL, DECEMBER 19, 2023

ÉCOLE DE TECHNOLOGIE SUPÉRIEURE
UNIVERSITÉ DU QUÉBEC

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ACKNOWLEDGMENTS

I would like to express my sincere gratitude to the following individuals and institutions whose unwavering support and guidance have been instrumental throughout my academic journey.

I extend my deepest appreciation to my family for their unwavering support, both financially and emotionally. Their belief in my aspirations has been a constant source of motivation, and I am profoundly grateful for their sacrifices and encouragement which I was lucky enough to receive.

I am indebted to Professor Sylvie Nadeau for her pivotal role in shaping my academic pursuits. Her mentorship, patience, and friendship have not only enriched my scholarly endeavors but have also had a profound impact on my personal growth. I am truly fortunate to have had the opportunity to learn under her guidance. My sincere thanks go to Valérie Tuyêt Mai Ngô, research assistant and co-author of some of my publications, for her invaluable contributions to this thesis and research project. Her expertise and dedication significantly enhanced the quality of this work, and I am grateful for her collaborative spirit. David William and David Euloge have my sincere gratitude for helping with the design of the laboratory experiment.

I would like to extend my appreciation to ÉTS and Natural Sciences and Engineering Research Council of Canada (NSERC) for their generous financial support and access to the research infrastructure. This support has been essential in enabling me to pursue this academic endeavor.

This thesis would not have been possible without the collective support and encouragement of these remarkable individuals and institutions. Their belief in my potential has been a driving force behind my accomplishments, and I am deeply thankful for the unwavering faith in my abilities.

Modélisation et qualification du travail d'assemblage numérisé futur

Nasim KHODDAMMOHAMMADI

RÉSUMÉ

Au cours des dernières années, l'utilisation des dispositifs intelligents portables a gagné en importance dans diverses industries, promettant une productivité améliorée et des avantages ergonomiques. Ce mémoire présente une étude de recherche approfondie sur la mise en œuvre de lunettes intelligentes (lunettes connectées) dans la transition de l'assemblage manuel vers des systèmes d'assemblage hybrides complexes dans un contexte d'Industrie 5.0. L'objectif est d'aborder l'utilisabilité et les impacts de ces dispositifs intelligents dans les lignes d'assemblage hybrides et de rassembler des connaissances scientifiques et des données sur les aspects pratiques de l'utilisation de dispositifs intelligents dans de tels environnements. L'étude souligne l'importance de relever les défis posés par les lignes d'assemblage hybrides complexes et met en évidence l'utilisation potentielle des lunettes intelligentes.

L'intégration des lunettes intelligentes dans un environnement de travail complexe et hybride, intégrant des équipements mécaniques, pneumatiques et automatisés, est explorée du point de vue de l'ergonomie et des facteurs humains, ainsi que des considérations opérationnelles. Les lunettes intelligentes, malgré leur potentiel, ont été peu explorées en ce qui concerne leurs impacts conjoints micro/macro. L'étude a permis de mener une évaluation expérimentale (étude micro au niveau du poste de travail) en utilisant le cadre de Nielsen pour évaluer l'utilisabilité et l'utilité des lunettes intelligentes. Des scénarios réalistes ont ainsi été conçus pour un ensemble de tâches d'assemblage physique sur un moteur/turbine d'avion simulé. De plus, des instructions pour les scénarios d'assemblage ont été planifiées à la fois sur papier et sur des lunettes intelligentes à des fins de comparaison, ce qui a offert des résultats intéressants concernant la qualité et le temps. De manière approfondie, des analyses STAMP-STPA et FRAM (étude macro analyse systémique) ont été utilisées pour identifier les risques potentiels pour la sécurité et les défaillances possibles au sein d'un système complexe tel que celui-ci, ainsi que pour identifier les interactions et les dépendances entre les éléments du système et les conséquences potentielles des changements du système.

Les résultats expérimentaux indiquent qu'il n'y a pas d'amélioration de la qualité après l'introduction des lunettes intelligentes (lunettes connectées). Bien que les instructions manquées étaient les mêmes avec ou sans lunettes intelligentes, plus de boulons ont été laissés desserrés après avoir utilisé les lunettes intelligentes et il y avait légèrement moins d'erreurs d'alignement avec les lunettes intelligentes. La seule réduction significative du temps de réalisation de l'étude a été observée dans le scénario sans lunettes intelligentes avec outil pneumatique.

Les résultats de l'analyse systémique indiquent que la mise en œuvre de lunettes intelligentes dans les processus d'assemblage a entraîné des performances variables des travailleurs influencées par l'expérience et des facteurs environnementaux, soulignant la nécessité d'une formation complète et de mécanismes de retour d'information. Les problèmes de sécurité incluent le risque d'assemblage incorrect ou de produits défectueux dus à des erreurs de lunettes. L’étude souligne l'importance d'une meilleure clarté des instructions et d'une communication bidirectionnelle pour une sécurité renforcée.

Ces résultats fournissent des informations précieuses sur les considérations pratiques de la mise en œuvre de dispositifs intelligents dans de tels environnements et proposent des recommandations pour améliorer l'efficacité et l’efficience des travailleurs. Sans aucun doute, les lunettes intelligentes, malgré leur potentiel, ont été peu explorées en ce qui concerne leurs impacts conjoints micro/macro sur les indicateurs opérationnels et les facteurs ergonomiques/humains de tels systèmes d'assemblage. Les résultats pourraient servir de base pour les développements futurs et les optimisations dans l’utilisation de dispositifs intelligents, en espérant améliorer l'efficacité dans les opérations de lignes d'assemblage complexes et hybrides.

En conclusion, cette recherche contribue à la compréhension des défis et des opportunités associés à l'intégration de lunettes intelligentes dans les systèmes de fabrication complexes et hybrides, en mettant en évidence leur potentiel pour améliorer l’efficacité et l’efficience des travailleurs.

Mots-clés : industrie 5.0, systèmes hybrides, assemblage complexe, lunettes intelligentes, lunettes connectées

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ABSTRACT

In recent years, the utilization of smart wearables has gained prominence in various industries, promising enhanced productivity and ergonomic benefits. This dissertation presents a comprehensive research study on the implementation of smart glasses (connected glasses) in the transition from manual assembly into complex hybrid assembly systems in Industry 5.0.

The objective is to address the usability and impacts of these intelligent wearables in hybrid assembly lines and gather scientific knowledge and data on the practicality of utilizing smart wearables in such environments. The study underscores the significance of addressing the challenges posed by complex hybrid assembly lines and highlights the potential usage of smart glasses.

The integration of smart glasses into a complex hybrid work environment, encompassing mechanical, pneumatic, and automated equipment, is explored from both an ergonomics and human factors perspective, as well as operational considerations. Smart glasses, despite their potential, have been little explored with regard to their joint micro/macro impacts. The study conducted an experimental evaluation (micro workstation level study) using Nielsen's framework to evaluate the usability and usefulness of smart glasses. Realistic scenarios were designed for a set of physical assembly scenarios on a simulated plane engine/turbine. Furthermore, instructions of assembly scenarios were planned both on paper and in smart glasses for comparison reasons which offered interesting results regarding quality and time aspects of the work. Extensively, STAMP-STPA and FRAM (systemic macro analysis) analysis were used to identify potential safety hazards and failures within a complex system of such as well as identifying interactions and dependencies among system elements and potential consequences of system changes.

Experimental results indicate that there is no improvement in quality after the introduction of smart glasses (connected glasses). Although missed instructions were the same with and without smart glasses, more bolts were left loose after using the smart glasses and there were slightly fewer alignment errors with the smart glasses. The only significant reduction in completion time in the study was seen in scenario without smart glasses with pneumatic tool.

Systemic analysis results indicate that the implementation of smart glasses in assembly processes resulted in variable worker performance influenced by experience and environmental factors, highlighting the need for comprehensive training and mechanisms feedback. Safety concerns include the risk of incorrect assembly or defective products due to eyewear errors. The study highlights the importance of improved clarity of instructions and two-way communication for enhanced safety.

These findings provide valuable insights into the practical considerations of implementing smart devices in such environments and offer recommendations for improving worker efficiency and effectiveness. Undoubtedly, smart glasses, despite their potential, have been little explored regarding their joint micro/macro impacts on operational indicators and ergonomic/human factors of such assembly systems. The results could serve as a basis for future developments and optimizations in the use of smart devices, hopefully improving efficiency in complex and hybrid assembly line operations.

In conclusion, this research contributes to the understanding of the challenges and opportunities associated with the integration of smart glasses into complex and hybrid manufacturing systems, highlighting their potential to improve worker effectiveness and efficiency.

Keywords: industry 5.0, hybrid systems, complex assembly, smart glasses, connected glasses

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LIST OF ABREVIATIONS

AI	Artificial Intelligence
AR	Augmented Reality
DR	Diminished Reality
VR	Virtual Reality
OAS	Operator Assistance System
OHMD	Optical Head-Mounted Display
GAT	Gaze-Assisted Typing
SAR	Spatial Augmented Reality
FOV	Field of View
HF/E	Human Factors and Ergonomics
OHS	Occupational Health and Safety
FRAM	Functional Resonance Analysis Method
STAMP	System-Theoretic Accident Model and Processes

STPA	System-Theoretic Process Analysis
NASA-TLX	NASA Scenario Load Index
IOT	Internet of Things
Hz	Hertz
STD	Standard Deviation

INTRODUCTION

The concept of intelligent machines has developed over the years. First through fiction and imagination and then turned into actual projects and practical technologies during recent years. Perhaps a good example of this transition could be a paper done by Alan Turing (1950), exploring the mathematical possibility of artificial intelligence. Limitations such as computer systems capacity reduced the speed of the development. However, a great advancement has been made in the fourth industrial revolution, known as Industry 4.0 and now in Industry 5.0.

Industry 5.0, which is sometimes referred to as the Age of Augmentation, represents a human-machine collaboration between humans, wherein technology is designed to enhance and complement our abilities in a user-friendly way (Longo et al., 2020). This involves the leverage of collaboration between progressively powerful and precise machinery and the unique innovative potential of the human being, to a point that more specific intelligent devices are being used and refined in manufacturing. As an example, the role and impact of wearable technologies in today's life is undeniable. Meanwhile, the manual form of these scenarios will not be cut out completely, the human touch will still be needed under some circumstances such as low-volume productions. It can also be less cost effective to do assembly by hand. There are advantages over completely manual work which is why the approach is to have semi-manual sectors in some fields more than others. Although current technologies bring forth a unique set of challenges and complexities, ongoing research and development efforts will undoubtedly lead to advancements in these emerging fields and human judgment will undoubtedly play a crucial role in this process (Nadeau and Landau, 2018). Moreover, as collaborative systems become more advanced and affordable, their adoption rates in manufacturing experience a sharp rise (Kolbeinsson et al., 2017).

From the role of wearable robots in rehabilitation and recovery of lost human power to the need for continuous monitoring of various scenarios, wearable sensors and other wearables have infiltrated and improved our lives.

As the intricacy of products and manufacturing environments continues to rise, it is imperative to prioritize employee assistance. One solution to this challenge is the implementation of assistive technologies, which can aid in managing the growing complexity of industrial production and the expanding diversity of work scenarios (Mark et al., 2021). By augmenting human capabilities with these technologies, companies can optimize their operations and facilitate a more efficient and effective workforce. As the number of product variations increases, workers are required to undergo training more frequently due to varying levels of expertise and skills. Consequently, the growing complexity and heightened quality standards put an additional cognitive burden on employees, creating a demand for assistance systems (Pokorni and Zwerina, 2020).

CHAPTER 1

LITERATURE REVIEW

The aim of this review is to address the gaps in the literature regarding the particular subject of using intelligent devices in manufacturing. Furthermore, clarifying the unanswered or vague problems and given solutions. This review will critically evaluate the researches that have been done in this field which will result in answering some questions which include:

- What kind of intelligent wearables are used in manufacturing?
- What benefits and challenges intelligent wearables bring to the manufacturing and assembly sectors and which types are preferred over others?

Here we present the hypothesis based on the review of literature.

- Hypothesis 1. Smart wearables necessarily increase the quality of work
- Hypothesis 2. Smart wearables speed up manufacturing processes
- Hypothesis 3. There are no high stakes risks related to the usage of smart wearables

This review is dedicated to the effects of smart wearables, specifically smart glasses and usage of them in different aspects of manufacturing and assembly processes. The review ends with answering the review research questions, and a discussion of the review is done. More extensive review including other smart wearables is included in annex III.

1.1 The concept of smart wearables in manufacturing and assembly

Assembly systems are currently undergoing substantial modifications as a result of shifting market conditions and drastic shifts in existing technologies. It is noted that assembly systems that can adapt and change need plans and models that can change accordingly too (Bukchin and Raviv, 2017). In addition, the most adaptable element and a must for flexible manufacturing will still be the humans. As it is vivid and mentioned in literature that from stationary computers and laptops, we have transitioned to the era of wearable devices, which users can carry with them at all times (Dvorak, 2007). The concept of smart wearables refers to any electronic intelligent device that could help humans with a more efficient productivity or safety by wearing them on the body. The reason why smart wearables are called “smart” is due to the fact that they can be adjusted to the user’s needs (McCann and Bryson, 2009). Smart indicates that the wearable devices can provide intelligent services such as details gathered from their environment, carrying out critical data treatment and delivering them, while being a functional part of a bigger system (Caramés and Lamas, 2018). Assistant systems are sometimes referred to as Operator Assistance System (OAS) (Moencks et al., 2021). There seems to be a lack of work in utilization of these technologies in different scales and organizational levels that needs to be worked on (Moencks et al., 2020). Moreover, there is a lack of studies that focus on user acceptance and improving their experience with these devices. It is concluded that the ergonomics of a product have an impact on user acceptance (Eswaran et al., 2023).

In Aerospace Assembly Processes we can see a clear need for more accurate measurements with the use of robotic solutions (Torres et al., 2021). As the study suggests, the industry will see less of the lowlights of the traditional assembly processes such as modifying and changing requirements. These elements are remarkably reduced with a major accuracy positioning of the components. However, many aerospace assembly activities will stay manual, wherein the complexity of an assembled item has a tendency to be high. The introduction of assembly guidance systems has the potential to enhance worker performance while reducing errors in the assembly process. Furthermore, with frequent production variations the ability of robots is limited in production and artificial intelligence (AI) will not be able to simply overcome this problem. Hence, when frequency and variation are important parts of a system, humans have greater performance than robots (FoX and Kotelba, 2019).

In manufacturing situations that involve high complexity and low volume, skilled workers are still necessary (Lagomarsino et al., 2021). Manual assembly is a vital component of the manufacturing process that involves workers in different cognitive demands (Brolin et al., 2017). This is where smart wearables act as a form of robotic device that can be worn and be combined and linked closely to human activities. Furthermore, at the end of a production line, manufacturing companies need a final validation and testing process that is achievable with intelligent wearables, which will be discussed in this review and show examples of improvement in the quality of work with a new approach.

This review seeks to demonstrate the documented usage of intelligent wearable devices in manufacturing and illustrate the way they are helping assembly systems and what advantages and challenges they bring. Moreover, the impact of smart wearables on quality of work, scenario time and risks are verified and expressed.

1.2 The variety of smart wearbles and users

Datagloves, smart glasses, and exoskeletons (e.g., upper limb and chairless chair) are all technologies designed to enhance the comfort and productivity of semi-manual assembly systems. In what follows, we have put the focus on smart glasses and discussed the advantages and challenges of using them in various sectors and industries, as well as the existing research that is available and relevant. The literature review done on datagloves and exoskeletons is included in Annex3 for further information.

1.2.1 Smart glasses

Wearable devices featuring many sensors, a built-in processor, and a digital display for observation and interaction are known as smart glasses. These features are useful with extending the scope of smart glasses to many industries that are more focused on engaging users. The product offerings of manufacturing companies have significantly expanded due to global competition. This has resulted in enhanced complexity for assembly workers, which has an impact on quality. However, by making the assembly scenarios easier, this problem can be mitigated to some extent (Falck et al., 2016). By using appropriate technology to transmit data from an existing database, smart glasses are able to present a computer display in front of the user's eyes, providing easy access to the needed information. Enhancing the existing actual environment with knowledge provided by an information system is the reason why they often come with the term "Augmented Reality". The screen can be a distinct element brought to the eye sight or it can be projected / reflected on the lens of glasses. The most crucial aspect is that the users may monitor their surroundings without being distracted when they are not in need of the smart glasses' support. Moreover, users could engage with smart glasses in different ways such as AR (Augmented Reality), which has the goal to create virtual items that the viewer can see alongside the real-world, displayed to the user through an alternative light source that doesn't obstruct their line of sight. DR (Diminished Reality), is another method which is almost the same as AR with the difference that it filters the light that is reflected by some objects toward the eyes and deletes those objects from the real world for the user. The third way is through VR (Virtual Reality). In this case, the user only sees the virtual environment that has been created for them to experience and interact with. Various smart glasses incorporate diverse technologies, yet they all share the commonality of not solely presenting virtual objects on a separate display, distinct from the immediate physical surroundings (Spitzer et al., 2018). In this approach, user activities have no effect on the screen display, whereas in AR systems, user actions have an impact on the virtual environment. It is interesting to mention that some studies that have used smart glasses, only used the glasses in a connective way to provide user with scenario information (Smith et al.,2021; Żywicki and Buń., 2021).

Numerous methods have been created to date that allow us to engage with smart glasses. Certain solutions have utilized optical principles to project information onto the glass lens in front of the user's eye, whereas others have opted for LED-based approaches, microphones, and mobile devices to make smart glasses link and interconnect with the user. An approach known as the "pointing technique", is used to point at things that we want to accomplish specific activities on them. As a result, there are at least three such approaches for pointing at items in the wearable technology category and more specifically smart glasses: pointing at the object with only looking at it, with laser pointer, and pointing at the object with a crosshair on an Optical Head-mounted Display (OHMD). Interacting with smart glasses is possible through hand gesture by pointing at objects viewed by the user as well. This method is known as air-writing (Chen et al., 2019; Tung et al., 2015). A model is presented and used for real-time detection and localization of hand regions and fingertips. The model can accurately work with 640x480 RGB images at 38 frames per second. The input approach evaluates fingertip trajectories as character strokes and then identifies written letters. Within the device, there is also a pointing mechanism for pointing at objects in order to communicate with the glasses. Text entry could also be done by PalmType. In this method, palms are used as a keyboard which increases the speed of text input compared to using a physical touchpad (Wang et al., 2015).

Another Google Glass-based engagement approach includes a camera and an OHMD. Due to computing restrictions in Google Glass, the images are transferred to a computer over the local network. A crosshair is placed in the corner of the OHMD so that it interferes with the user's vision as little as possible (Kim et al., 2019). Several experiments on this method revealed that a very low error can be accomplished by employing the method. An interesting feature of smart glasses could be eye tracking. This functionality elevates the user experience to the next level. This feature's goal is to detect and locate the element that the user desires to choose, which is prompted by eye movement. This feature can also be used to monitor an employee's eye movement. This will help establish whether the employee is fatigued and needs to take a break, or if the individual has completed all of the job and is not occupied. Integrating smart glasses into the architectural planning of a construction site can aid engineers in detecting construction flaws and help workers prevent mishaps like inadvertently drilling into water pipes (Abdelrahman et al., 2015). These are only a few of the many possibilities for smart-glass applications.

A study in 2019 introduced text input method for users which includes eye movement and touch at the same time. This concept known as Gaze-Assisted Typing (GAT) has demonstrated that when compared to touch-only or eye movement only text entry, can ensure faster on-glass text entering (Ahn and Lee, 2019). One method for smart glasses input is speech recognition. Smart glasses employ machine learning to generate preconfigured input messages, drawing insights from user behavior and data sourced from previous interactions. These messages typically highlight the most frequently chosen menu item. When a user remains inactive, the system resorts to these input messages to proceed to the next scenario. However, a major drawback of relying on these preconfigured messages is the potential for delivering undesirable messages, requiring consistent user intervention to fine-tune the machine's behavior over time (Chen et al., 2019).

Other great input possibilities are facial gesture (Masai et al., 2020) and head gesture. A study in 2016 used the input method of Head Gesture Recognition, which is precise in a variety of activities, regardless of noise. This method has a near-perfect gesture recognition (96%) which can accept authorized personnel in about 92 percent and reject unauthorized users in nearly 99 percent for authentication. Because of their high electromechanical sensitivity, motion sensors on glass can identify all types of head movements. In some settings, using the included touchpad or voice instructions to operate glass may be considered improper or even disrespectful; in these cases, the head gesture system is advantagious compared to traditional input options. Furthermore, the head gesture user interface can authenticate users, increasing the device's security (Yi et al., 2016). Gesture interactions are also broadly used in assembly scenarios of a production line because they provide a natural environment for the user engagement with the device (Malik and Bilberg, 2019). A recent study introduced an interaction method using a smart strap (StretchAR) that gives the user a “eyes-free” experience (Paredes et al., 2022). The strap can be put on any part of the body with high detection accuracy.

Table 1.1 shows different input methods in smart glasses describing their advantages and challenges as well as the technology used.

Table 1.1 Different Input Methods used in Smart Glasses
Adapted from Aman et al. (2021, p. 17)

SR No.	Method	Challenges	Advantages	Technology Used
1	Voice Recognition	Can be noisy in shared environments	Provides a hands free experience	Microphone
2	Hand held device such as smartphone	Need of extra equipment	Less chances of error in providing input to the glass or accessing information	Depends on the device which is being used
3	Touch	User taps on bodypart or wearable devices	No need to carry any extra equipment	Touchpad
4	Head Gesture	Accuracy and effectiveness as limited amount of inputs can be given	No need for additionalsensors or hardware/ Increased security	Camera and sensor-based facetracking system
5	Palm Type	Feasibility	Provides visual feedback and detects users finger position	Network of infrared sensors mounted to wrist
6	Air writing	Accuracy of fingertip localization	Interacts with the system using simple Gestures	Google API

Studies regarding usage of smart glasses for “Picking and Putting scenarios” have revealed the concerns around the comfort level of these devices for four-to-eight-hour shifts (Smith et al., 2021). Also, illustrating the decrease in scenario time as well as a better identification of the material to be picked has been a concern (Żywicki and Buń, 2021). Table 1.2 illustrates various Smart glasses with their specifications.

Table 1.2 Illustration of various Smart glasses
Taken from Aman et al. (2021, p. 20)

SR No	1.	2.	3.	4.
Product Name	VuzixM300 XL Smart glasses	Oculus Rift	Reckon MOD	Google Glass
Weight	Various wearable setup choices exist for attaching the Viewer and battery, each with distinct weight characteristics	470g	65g	50g
Processing	Dual Core Intel AtomCPU	Inteli5- 4590 / AMD Ryzen 5 1500X or Greater	Not disclo sed	1.2 Ghz Dual-core ARM Cortex- A9 CPU,16GB
Display	Occluded LCD Display	Two displays placed in front of lenses	LCOS Display	Color prism projector with resolution
Sensors	Gesture control, voice control, touchpad, gyroscope, accelerometer, magnetometer, proximity	Accelerometer Gyroscope Magnetometer	Displayin g maps and performan ce	Microphone, accelerometer, gyroscope, compass
Communication	Bluetooth 4.0, Wi-Fi	Bluetooth and Wi-Fi	No requireme nt	Bluetooth and WLAN 802.1 b/g
Camera	10-Megapixel Camera Sensor	No Use	HD Video	5MP
Interaction	Hand free gestures, Touch pad	Hand held contro ller	Through a wrist remote	Long touchpad that supports
Audio	Integrated Speaker 98dB	3D HEAD SETS	No Audio	Bone conduction

SR NO	5.	6.	7.
Product Name	The Turing Machine	Focals by North	Vuzix Blade smart glasses
Weight	More than10 Kg	72.57g (focals)	93.6 g
Processin g	Used a computer	Qualcomm APQ8009w with Arm Cortex A7	ARM Cortex-A53
Display	See-through	Holographic display	Vuzix Waveguide
Sensors	Trackpad, handheld computer, GPS	9-axisIMU, ambient light sensor, proximity sensor	Gesture control, voice control, touchpad, gyroscope,
Communication	Not available	Focals smart glasses: Bluetooth 4.2Loop ring: Bluetooth LE	Bluetooth, WiFi
Camera	Not available	Built in Camera	8 MP
Interaction	Handheld controls	Through a Ring	Handfree gestures, Touchpad
Audio	Not available	Integrated microphone, speaker	Stereo Integrated speakers

SR No	8.	9.	10.	11.
Product Name	SONY Smart Eye Glass	META2	GlassUpF4	Epson BT 300
Weight	77g	420g	Not disclosed	69g
Processin g	Not disclosed (Still in development)	CPU: Intel Corei7-6700(HQ), AM D	CortexA9 processor	Intel® Atom™x5 1.44GHz QuadCore
Display	Binocular, See-through, Monochrome	AR Display	Monocular display	Binocular See- through- OLED
Sensors	Includes accelerometer Gyroscope,	Integrated Optical and inertial sensors	Augmented reality goggles	9 axis motion Sensors
Communication	Wireless LAN and Bluetooth connection	Through HDMI	WiFi and Bluetooth connectivity, Communication onVOIP	Bluetooth, WiFi
Camer a	3 MP	720p front-facingRGB camera for mixed	5 MP	Has 5 million pixels
Interaction	Through controller	Sensor array for hand interactions and	A box full of control equipment	Hand remote
Audio	Inbuilt speaker	4 built-in surround sound speakers	Built in speaker	Speaker

An interesting recent literature review focusing on the maintenance aspects in manufacturing showed increase in quality and efficiency of work while using AR and VR (Buettner et al., 2022). Critical challenges regarding hardware and software elements as well as possible usages of AR and VR technologies in different aspects of manufacturing industry have been demonstrated in another study (Eswaran and Bahubalendruni, 2022). This study indicates how the usage of this technology can open the door for industries to adopt other advanced technologies as well. Moreover, one study concentrating on less skilled workers explained the benefits of AR in simplifying the work and usage of a tool specially in a shortage of employee situation (Szajna and Kostrzewski, 2022).

When it comes to the challenges of smart glasses, it is indicated to be, among others, the limited field-of-view (Simões et al., 2019). This issue disrupts the proper synchronization of virtual and real environments (Danielsson et al., 2020). In that regard, in some studies, projection-based instructions have been proposed as a possible alternative (Rodriguez et al., 2015; Sand et al., 2016). However, it is shown that projection-based instructions provide minimal advantages in training scenarios, and the training outcomes fall short in terms of speed and accuracy in recalling information compared to personalized training after a 24-hour period (Büttner et al., 2020). All projection systems seem to need further improvement in different parts such as holographic display, calibration and target tracking (Ngankam, S.-G, 2023). Another concern stated by Tang et al. (2003), is the distraction of the user by overwhelming details or cued areas of the instruction in the AR system and neglecting the real environment and missing other information. Discomfort in the form of visual fatigue (Han et al., 2017) and the weight of the device (Yan et al., 2018) are some ergonomics challenges one faces when using them. Another interesting challenge is to know if the image illustrated on the smart device is perceived differently (Han and Suk, 2019). According to the findings of a study which digged into concerns for thermal radiation and heating associated with the usage of these glasses, specific models of these devices have the potential to cause an increase in forehead temperature when used during the process of assembling objects (Laun et al., 2022).

Furthermore, advantages of using VR and AR in assembly and maintenance can be outlined as; decrease in training time (Peniche et al., 2012; Hořejší, 2015) and decrease in cognitive load and errors by 82% (Tang et al., 2003). Use of AR has demonstrated positive results in laptop assembly as a part of a complex assembly (Chiew and Sung, 2021) and also for training phone repair operations (Lopik et al., 2020). Use of AR is found to decrease cognitive load and time as well as increase of focus on the assembly (Khuong et al., 2014; Henderson and Feiner, 2011; Chiew and Sung, 2021). Assembly of complex parts (Suárez-Warden et al., 2015) and wire bundles (Thomas et al., 1992) in aircrafts with the use of AR have also proven to be less time consuming than with paper instructions. It would be interesting to mention that during assembly scenarios, utilizing speech recognition technology seems to be more desirable compared to having to focus on locating specific keys on a keyboard (Chiew and Sung, 2021). Spatial Augmented Reality (SAR) was used in 2022 in a study for prefabrication of wall elements resulting in reduction of time and workload but errors did not reduce significantly (Bartuska et al., 2022).

As described, there is a variety of input approaches for AR and VR devices that could be used for different purposes and work situations which have their own advantages and challenges. Overall, reading on the go is a challenge when using smart glasses; walking has a bad effect on reading, regardless of whether you are using a smartphone or smart glasses. It has an impact on comprehension and workload (Blehm et al., 2005). Blehm et al., 2005 has also demonstrated that unlike all other wearables, the technology is customised to the features of the eye. Risk of Computer Vision Syndrome, which results from looking at a point closely for a long period of time must be considered as well.

When the eye remains under prolonged strain, the eye muscles tend to tighten and struggle to return to a relaxed state for a while, thus inducing fatigue in the user. Table 1.3 summarizes the advantages and challenges discussed above of smart glasses.

Table 1.3 Advantages and challenges of smart glasses

STUDY	ADVANTAGES
(BUETTNER ET AL., 2022) (REVIEW STUDY)	Enhanced productivity
(AHN AND LEE, 2019) (CHEN ET AL., 2019) (MASAI ET AL., 2020)	Hands-Free operation by various input methods
(PENICHE ET AL., 2012) (HOŘEJŠÍ, 2015)	Decrease in training time
(TANG ET AL., 2003)	Decrease in cognitive load
(TORKUL ET AL., 2022)	Real-time monitoring and assistance
(MASAI ET AL., 2020)	Improving accuracy and efficiency
STUDY	**CHALLENGES**
(SIMÕES ET AL., 2019)	Limited Field-of-View
(DANIELSSON ET AL., 2020)	Distraction and neglect of real environment
(BLEHM ET AL., 2005)	Visual fatigue and discomfort
(BLEHM ET AL., 2005)	Comprehension and workload
(ESWARAN ET AL., 2023) (REVIEW STUDY)	Perception differences
(LAUN ET AL., 2022)	Thermal radiation and heating

1.3 Discussion

One significant aspect of using smart wearables is to guarantee that they are utilised properly. Achieving this involves ensuring that the technology is both user-friendly and indeed essential to be used, thus becoming a practical working tool (Barata and Cunha, 2019). Because of operator dissatisfaction and a decline in workstation efficiency, integrating AR devices into production contexts is proven to be challenging (Baslé et al, 2021). It has been demonstrated that for the improvement of a human-machine interface usability, the technology needs to be human-centered (Malik and Bilberg, 2019; Cimini et al., 2020; Kumar and Lee, 2022). Based on how quickly the user perceives a certain sensation and responds appropriately, scenario performance varies. As a result, in order to interact with the technology, the user must completely comprehend how it operates and the design principles must take into account both cognitive and physical factors (Kumar and Lee, 2022).

The complexity of a system brings challenges and achieving sustainable operations is heavily reliant on human-centered factors (Bednar and Welch, 2020; Ngoc et al., 2021; Moencks et al., 2021). In that regard, one of the challenges to overcome involves ensuring that the design of the workstation adequately considers the user-friendly aspects and places them at the forefront (Grandi et al., 2019). Complexity of an assembly could have effects on; time, cost, quality and ergonomics (Falck et al., 2014).

In regards to user acceptance, it has been demonstrated that if the assistance system gives thorough but not specifically tailored instructions adapted to the user while in use, the worker may feel as though their range of action is limited (Burggräf et al., 2021). A literature review study demonstrated that researchers often do not study user experience aspect of using VR and AR technologies (Santana et al., 2021). The reason is possibly because most applications used in smart glasses are designed to answer specific research questions which are not considering the user experience aspect. Lack of user acceptance in assistant systems (Pokorni et al., 2020) as well as emotional and social impacts of a system are considered to be valuable criteria in determining potentials of a digital assistant device (Pokorni and Constantinescu, 2021).

Most smart glasses users consist of professionals who anticipate benefiting from the technology's 'hands-free' attributes. Using technology for cognitive augmentation without sustainability considerations could lead to a risk of losing certain skills, like navigation, as we become overly reliant on it, or assign critical duties to less skilled employees (Spitzer et al., 2018). In 2020, a survey was conducted aspiring for an accelerated application of augmented reality smart glasses (ARSG) for manufacturing operators by reviewing categories that are important to them. ARSG is a wearable device that can combine virtual and physical data in the user's field of view (FOV), according to the paper's authors (Danielsson et al., 2020). The key conclusions provide a deficiency of assembly instructions and their design, a restricted field of view for ARSG, and guidelines for formulating instructions focusing on delivering contextually relevant information while minimizing reality disruption. A comprehensive evaluation of strategies for distributing the weight of ARSG, further enhancing sensor capabilities to facilitate improved interaction, and addressing scenario management are among the challenges highlighted in the review. As a matter of security for users of smart glasses, Face Recognition has been introduced with high accuracy. However, challenges such as facial expressions and light intensity need to be noted (Khan et al., 2019). As worker performance aspects of using AR and VR technologies was studied in 2022, it showed strong links to the user's cognitive, psychosocial, perceptive, and physical characteristics (Di Pasquale et al., 2022).

Nowadays, the industry is progressively transitioning from both manual and entirely automated production approaches towards hybrid solutions (with both manual workers and automated/digital machines). This approach aims to bring industry closer to widespread acceptance and usage of these hybrid solutions. This technique leads to increased level of satisfaction and, as a result, greater acceptance of hybrid manufacturing systems. Even though recent research shows the potential of smart wearables in enhancing manufacturing operations, more research is still required. According to the literature, the challenge of obtaining a balance between functionality and wearability at a low cost must be overcome in order to achieve large scale usage. In addition to this, some illnesses are likely to develop. Prolonged use of eye-sensitive technology affects both the users' brains and their eyes (Mann, 2013). How these technologies affect different body parts is therefore an unresolved challenge. As wearables are becoming more popular, technologies are enabling the monitoring and improvement of human physical activity as part of integrated systems. A comprehensive examination of all relevant aspects is necessary in the design process, including technology, ergonomics, human factors, and validation techniques. Then it should be much simpler to look closer into the specific steps to overcome a particular problem for various applications. Pursuing this approach could yield to customized technology, making the incorporation of flexible technology into the smart wearable device simpler because it is predicated on both user and situational criteria.

The literature on intelligent wearables has demonstrated how these smart devices have quickly become a popular trend in industries as they have shown significant application value and have great untapped potential. According to the findings, there is widespread interest in developing sensor systems that can collect data and information in real time or after usage, as well as a strong focus on ergonomic based risk factors such as poor posture.

Three main smart wearables (smart gloves, exoskeletons (Active & Passive) and smart glasses (VR & AR)) were under study in this thesis which gives an answer to the question of variety of smart wearables in use in the manufacturing sector. Also, the results of this review precises that the large majority of the proposed intelligent wearables are based on sensor systems. For the usage and application of these technologies; the preferred type of technology seems to be the sensor based which could be a result of the designers' ability to choose from a broad set of sensors with different features surveil the variables which are being monitored. Another important factor to consider during the design stage is where the sensors will be placed. The location of sensors and components is determined by the assignment given to the user.

To answer the question on the challenges; one important challenge facing the use of smart wearables seems to be the user acceptability criteria. A user must feel comfortable physically to wear the device for a long time as well as having a good experience with easily interacting with the device if needed. Figure 1.1 shows a well known ergonomics/ human factors (HF/E) model for system acceptability. As far as we know, there are no micro/macro study on the impacts of introducing smart glasses in a complex hybrid assembly system.

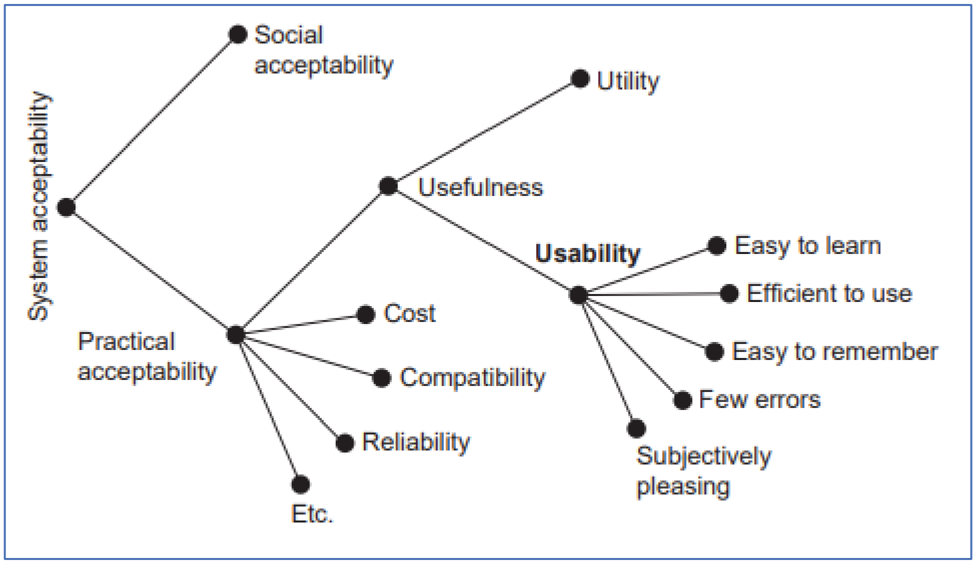

Figure 1.1 Model of the attributes of system acceptability

Taken from Nielsen (1993, p. 25)

- Hypothesis 1; Smart wearables necessarily increase the quality of work is rejected. Because as it is mentioned the result of using smart wearables depends on the different models used.
- Hypothesis 2; Smart wearables speed up manufacturing processes cannot be rejected completely. For speed of a scenario other criteria such as the experience of a user and model of the device are to be considered as well.
- Hypothesis 3; The statement that there are no high stake risks related to the usage of smart wearables, is rejected.

For smart glasses; the visual feed could be improved and adding new options for easier use could be reworked. Future research should focus on developing a clearer definition of intelligent wearables in terms of practicality as well as including new models and a more extended variety of samples. A device being adaptive is different than it being adaptable and there seems to be a lack of clarification in the benefits and the efficiency of smart wearables which needs to be addressed. Accurately selecting the scenario in which wearing the smart wearable could be actually beneficial and should not be used for just any and all scenarios.

Research question

The review of literature relevant to the study made it possible to identify different approaches to the usage of smart glasses in the manufacturing sector. However, it has been noted that user experience and acceptance still needs to be addressed (Santana et al., 2021). The research question is as follows:

"What are the impacts of using smart glasses in complex hybrid assembly lines?"

To answer the research question and discuss the hypothesis, we adopted the methodology presented in chapter 2. This methodology has two parts: 1) micro analysis - usability testing on a test bench simulating realistic assembly scenarios in a hybrid system, referred to in this thesis as the workstation (see section 2.2); 2) macro analysis - systemic analytical analysis (STAMP-STPA, FRAM) of impacts of using a smart glass (in a connected way) in a complex hybdrid assembly system (see section 2.3).

The hypothesis of part 1 of this research are:

1. Choice of tools has a significant impact on quality and time
2. Usage of smart glasses significantly increases quality of work.
3. Usage of smart glasses significantly reduces scenario time.

Choosing the right tools, quality and time is critical for organizational success, as they interconnect to influence productivity, reputation, and customer satisfaction. The significance of each factor is contingent upon the strategic objectives of the organization, influencing its overall effectiveness and competitive position within the manufacturing sector (Torres et al., 2022).

CHAPTER 2

METHODOLOGY

2.1 Critical review of literature

A search of the English literature was conducted in ScienceDirect, Google Scholar and Semantic Scholar databases, using the following keywords: digitalized assembly, smart wearables, flexible manufacturing and semi-manual assembly systems. Studies using smart wearables but not in the manufacturing sector were excluded unless they had results directly regarding the general use of the device or a useful detail. Peer reviewed studies published in conferences or journals were chosen. Papers that we could not have access to the full text were excluded. Coverage of the relevant literature was maximized through the snowball effect. Works published in English language in the last seven years (2016-2023) was employed but relevant and interesting publications have been also added from previous years. The literature was then sorted according to the three main intelligent wearables (smart gloves, smart glasses, exoskeletons) studied at the Applied Human Factors Lab. For a published version of the literature review please refer to ANNEX III, Canadian Association for Research on Work and Health (CARWH) peer reviewed poster.

Limitations

It must be mentioned that some limitations exist in conducting this review due to the taken approach and the chosen keywords in limited database search. Also, most of the publications used in this review have been only focused on industry 4.0.

The methodology of the research project consists of two parts: a laboratory experiment and an analytical analysis of both the workstation and the whole complex hybrid assembly system, using systemic modelling FRAM and STAMP-STPA. Our experiment looks into the micro aspects (workstation) while the analytical methods look at the macro aspects, the 4.0/5.0 assembly system including the workstation (laboratory experiment). The complexity linked to the interconnections of different functions of a complex hybrid assembly system cannot be represented by the Applied Human Factors Lab assembly test bench.

2.2 Part 1: Micro analysis (workstation)

Usability testing

For this study, a laboratory experimental research design was selected and received approval from the Ethical Committee of École de technologie supérieure in July 2022. The renewal of the approval was granted July 19th, 2023 for one year. This approval can be found in Annex VIII.

Intelligent wearables have quickly become a popular trend in industries as they have demonstrated significant application value. Nowadays, the industry is gradually shifting away from either manual or fully automated production and towards hybrid solutions (manual + automated + intelligent tools in the same system). The proposed approach in this project aims to bring industry one step closer to widespread acceptance and usage of human–intelligent devices collaborative solutions. The objective of this experiment was to gather scientific knowledge and data on the impacts of smart wearables in complex assembly lines. To answer our research question regarding the impacts of using smart glasses in complex hybrid assembly lines, we aim to pin point advantages and limits of the usage of these intelligent devices. In doing so, we integrated them, in a connected way, into a hybrid workstation (mechanical, pneumatic and automated equipment) in order to study the impacts in an OHS perspective as well as operational aspects.

Furthermore, we demonstrate, in this experiment, how the introduction of smart connected glasses and choice of tools affect quality of work and scenario time. This is directly linked to our hypothesis in the discussion section of chapter 1.

We recruited 16 human participants from ÉTS campus through ads on ÉTS televisions and Interface as well as an information meeting. Afterwards, participants interested were invited to a preliminary meeting to read and complete the consent form. A lab appointment was taken when the Physical Activity Readiness questionnaire (2022 Par-Q+/2022Q-AAP+) (ANNEX IX) for evaluating participants' health and consent form (ANNEX X) were completed. In the end, 10 participants were able to participate and completed the whole experiment. The suitable height of the jig for the sample of participants (Table 2.1) was determined by calculating the average height of the participants' floor to elbow plus the handle of the ratchets used.

Table 2.1 Sample of participants

Number of participants recruited	Exclusions and dropouts	Number of participants in the experiment	Age	Gender	Experience	Average height; floor to elbow
16	6	10	22-51	5 male, 5 female	Only one experienced participant	105 cm

One meeting per participant was necessary to collect the research data needed. During those tests, participants were working in a lab environment.

Activities the participant needed to complete:

Table 2.2 Description of scenarios and steps

Assembly	Scenario	Tools	Vuzix Glass	Number of participants
1	1	Manual ratchet		10
	2	Air ratchet		
2	3	Manual ratchet	X	10
	4	Air ratchet	X	

The participants had to complete two instructional methods with two scenario type. This resulted in 40 trials (10 participants * 2 instructional methods * 2 scenario types). Each participant had to complete four scenario performance for this experiment, each with 15 repetitions. (Table 2.2). Each scenario took approximately 1 minute to finish and was repeated 15 times. There was a 10 minutes break between each scenario.

In the first two scenarios, no smart wearables were used and the assembly was exactly the same for all scenarios. Two scenarios were using one intelligent glass and a computer. Instructions in glasses were put through the glasses' software that was connected to the software's website and participants could move back and forth in the instructions with a key on the glasses. The components to assemble were L shaped brackets which need to be assembled with bolts on the provided jig as shown in Figure 2.1 It needs to be mentioned that there is a loose tolerance between the holes on the plate and the diameter of the bolts. This tolerance generates uncertainty in assembling and makes it more complex when assembling or fastening bolts. The brackets were positioned using a combination of visual and tactile references. While it may seem that our experimental setup represents a conventional single workstation test bench, it is essential to underscore that the complexity in our study arises from the dynamic decision-making processes involved. Participants are faced with intricate choices that extend beyond the physical assembly process. Specifically, they are scenarioed with selecting appropriate tools and bolts, determining the optimal order and position of part assembly, and making individualized pattern decisions. This multiplicity of choices and decision-making intricacies collectively contribute to the complexity of the assembly system under investigation.

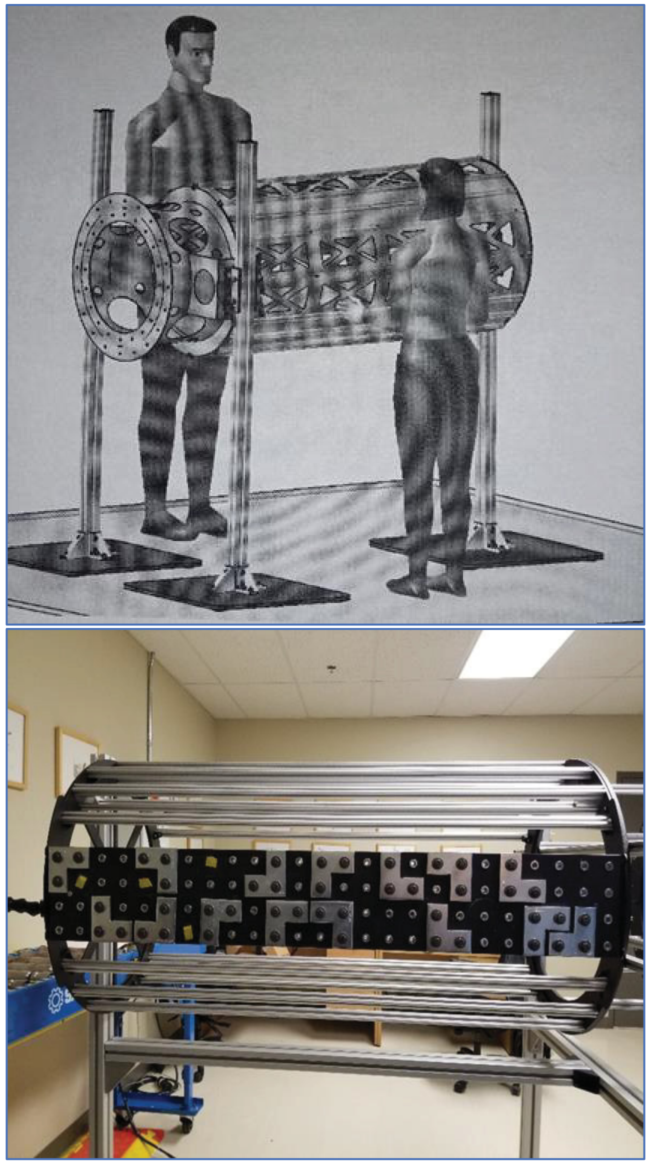

Figure 2.1 Assembly jig and L-shaped brackets

A short training on how to use the tools and components was given before starting the test with each participant. It should be mentioned that no time limits were imposed on participants during the study and there was a ten-minute break between each scenario. In the first scenario of each assembly, the participant used a manual ratchet to assemble the brackets with bolts which was provided on a conveyor. The bolts provided were in two different sizes and the participant had to choose the correct size according to instructions given as pictures. The second scenario of each assembly used an air ratchet and in scenarios 3 and 4 intelligent glasses and eye-tracker were used. The alignment of the brackets was based on pictures given on a piece of paper or in the smart glasses. Also, the border of the assembly plate was set as tactile cues to align the brackets with the top and bottom. Figure 2.2 illustrates the correct order in which brackets were to be assembled on the plate. This order was the same for all scenarios.

Figure 2.2 Order of brackets on the plate

Instructions given on paper and through smart glasses:

- Stand between the jig and the work table.
- For this assembly, you need manual\air ratchet.

- 45 bolts, 15 brackets (Shown in the picture).
- *The bolt size and shape are illustrated and are important.

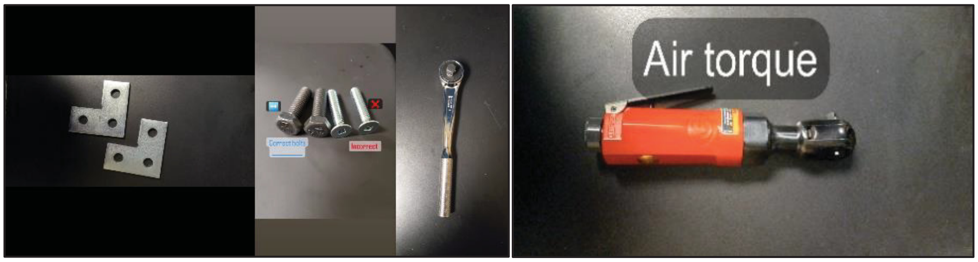

Figure 2.3 Pictures shown in smart glasses for tools

- Take a bracket, wait for the bolt box to arrive to you on the conveyor, put the box on the table and pick the right bolts (3 for each bracket).
- Adjust the bracket on the black plate making sure the top or bottom of the bracket is aligned with the top or bottom of the plate (see picture).

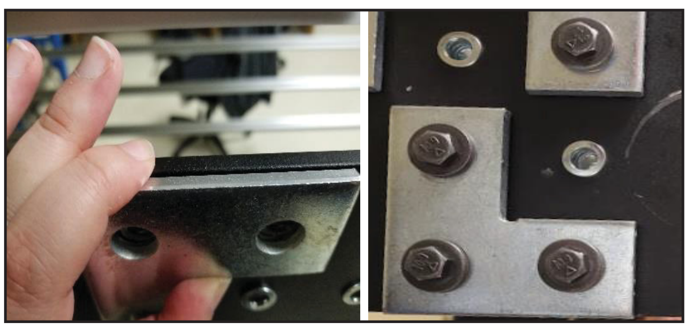

Figure 2.4 Alignment of brackets

- Make sure you follow the pattern on the next image for the placement of the brackets.

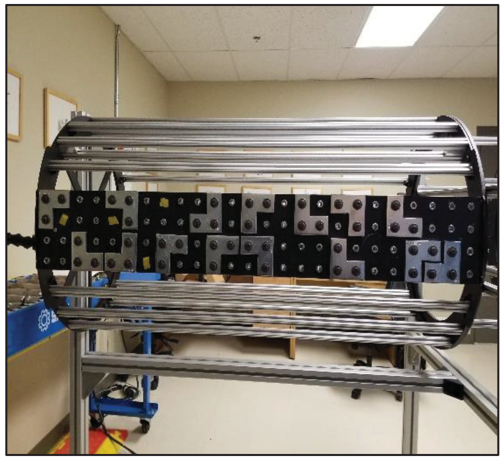

Figure 2.5 Order of brackets to be assembled

- Take the ratchet and fix the bracket in place.
- Repeat previous steps until you have assembled 15 brackets on the black plate.

Equipments used for the assembly activities:

Intelligent tools:

One smart glass (one VUZIX M400 smart glass (AR glasses)) which was programmed according to the needs of this study by a graduate student) was the smart wearable that the participants used during assembly. These smart glasses, eventhough were capable of being used as VR glasses, were used in only a connected way and did not transfer any data from the user. The assembly scenarios were done on a jig designed for and at ÉTS. Tools and components used in the assembly scenarios include:

Classic working tools:

One Mc Master 3/8" Manual Ratchet and one Grainger 3/8" Pneumatic Ratchet as shown in Figure 2.6, are used for the assembly. 20 Strut Channel Bracket Elbow and 27-Piece Premium 6-Point Socket Square Drive are also used in the experiment. A floor roller conveyor Sadler which has been automatized was also used.

Figure 2.6 Manual and air ratchet

Measuring tools:

A Pupil-labs core eye tracking system was used on the eyes of the human participants and was worn under the smart glasses. Before beginning the experiment, each participant was asked to view specified targets on reference images to calibrate the eye-tracking gaze data. For calibration, we adjusted the gaze cursor to the participants' gaze points in the reference image.

The eye tracker (Figure 2.7) consisted of a world camera and two eye cameras. The world camera was a 180° adjustable camera with a 60 Hz sampling frequency and a 1280 × 720 pixels resolution. The eye cameras are adjustable in the front/back direction and are capable of recording the user's gaze point, pupil behavior and blink with 200 Hz sampling frequency and a 192×192 pixels resolution. Pupil Core eye tracker was chosen due to its suitable features for manual assembly scenarios. However, we had to deactivate one of the Pupil-labs cameras to not interfere with the smart glasses screen. This action was approved by the Pupil-labs company and had no impact on results.

Figure 2.7 Left eye-tracker, right intelligent glass

Furthermore, two GoPro HERO3+ cameras were used, placed on both sides of the participant for monitoring the assembly and upper limbs movements. The cameras were also used for measuring time.

NASA Scenario Load Index (annex VII) was used as a short survey at the end of each lab meeting with each participant. NASA-TLX evaluates subjective workload perceived throughout scenarios to assess these scenarios. Results of the evaluation are presented in annex VII.

Statistical analysis

The analysis was done from the steady point of the assemblies which was identified after the calculation of the 40 learning curves.

Moreover, due to the nature of our experiment and the number of participants the paired T-Test was used for data analysis to show the significance of results for quality and time. Paired t-tests are suitable when participants are not divided into separate groups; instead, all participants are involved in one scenario and then another one. The extent of change between two scenarios is recorded for each participant. In such crossover test designs, a paired t-test is utilized to compare the changes induced by scenario A and scenario B within the same set of participants (Wilkerson, 2008; Kim, 2015).

Descriptive analysis is done for error type and patterns chosen by participants; one by one (assembling brackets individually) and grouping (fixing brackets in place in groups and then finishing the assembly using the tool for the whole group of brackets fixed).

For access to prelimimary results, we invite the reader to have a look at the CIGI-QUALITA-MOSIM 2023 peer reviewed conference paper in ANNEX II.

2.3 Part 2: Macro analysis (complex hybrid assembly system) using systemic analytical analysis

As we delve into the integration of smart glasses into complex hybrid assembly systems, a robust understanding of potential implications becomes paramount. To achieve this, we turn to two sophisticated systemic analysis methodologies: the Functional Resonance Analysis Method (FRAM) and the Systems-Theoretic Accident Model and Processes (STAMP-STPA). Our experimental setup, though confined to the workstation, necessitates a comprehensive examination of system functions' interconnections. Systemic analysis proves essential in uncovering unintended consequences, managing emergent behaviors, and predicting long-term effects associated with smart glasses integration.

This methodology exclusively leverages FRAM and STAMP-STPA due to time constraints, aiming to guide decision-makers in balancing production imperatives and occupational health and safety during the digitalization of assembly processes. The ensuing sections delineate the steps involved in applying these methodologies, offering clarity for readers less acquainted with these powerful analytical approaches. We invite the reader to consult the books of Hollnagel (2012) and Leveson and Thomas (2018) for more details.

As the experimental setup is limited to the workstation and the complexity linked to the interconnections of different system functions are not represented, a larger view is needed. A systemic analysis is crucial for studying the impacts of integrating smart glasses into complex hybrid systems due to its ability to provide a comprehensive and holistic understanding of the entire system. By examining the interactions and interdependencies between various components, it helps uncover unintended consequences and manage emergent behaviors that may arise from the integration. Moreover, it enables predicting long-term effects and facilitates continuous improvement as the technology and system evolve over time. In essence, a systemic analysis offers valuable insights and informed decision-making to ensure successful integration and management of smart glasses in complex hybrid assembly systems.

For over a decade, researchers have been concentrating on advancing more comprehensive methodologies in the literature (Holman et al., 2019). Two notable models have emerged as a result of this focus: FRAM, which draws from resilience engineering principles; STAMP-STPA, which is rooted in control theory (Adriaensen et al., 2019; Wang et al., 2019). In this study we will use STAMP-STPA and FRAM only as doing a triangulation was not possible time wise.

A systemic analysis using STAMP-STPA and FRAM modeling will guide decision-makers in choosing the means to deploy, to balance and optimize the imperatives of production and OHS on their path to process digitalization.

STAMP-STPA is a hazard analysis technique used to identify and understand potential safety hazards and failures within complex systems. It focuses on understanding the system's control structure, decision-making processes, and information flow to prevent hazardous scenarios. FRAM stands for Functional Resonance Analysis Method. It is a systemic analytical approach employed for comprehending and examining complex socio-technical systems. FRAM provides a holistic understanding of the complex hybrid assembly system, focusing on the interactions and dependencies among system elements. It helps identify emergent behaviors, adaptations, and potential consequences of system changes.

While STAMP-STPA is based on control theory, FRAM is based on resilience engineering (Adriaensen et al. 2019; Wang et al., 2019). These two approaches are viewed as complementary (Linhares et al. 2021) and require comprehensive information regarding the systems to examine (Linhares et al. 2021, Thatcher et al. 2020). FRAM stands out as the only model that takes into account the examination of positive aspects or "what went right." In contrast, STAMP-STPA, which is a method for conducting worst-case analyses (Baybutt in 2020), focuses on assessing potential failures or negative scenarios.

STAMP-STPA analysis comprises four steps, as defined by Ishimatsu et al. (2010):" 1) Review System Hazards and System-Level Safety Constraints. The analysis identifies potential system hazards and establishes safety constraints at the system level. Hazards are conditions or events that can lead to accidents, errors, or unwanted outcomes. 2) Define Safety Control Structure and how the system is intended to operate safely and effectively. This step involves identifying control mechanisms, processes, and control actions that are in place to prevent or mitigate hazards. 3) Identify Potentially Inadequate Control Actions. This step focuses on examining the potential inadequacies within the safety control structure, which can compromise safety. Four categories of inadequate control actions are considered:

- Absence of Necessary Control Actions: Identifies situations where a necessary control action is missing, leading to safety vulnerabilities.
- Incorrect or Unsafe Control Actions: Highlights cases where control actions are applied incorrectly or are unsafe, potentially resulting in negative outcomes.
- Incorrect Timing or Sequencing: Examines control actions executed too early, too late, or in the wrong order, which can lead to safety issues.
- Premature Termination: Addresses situations where a valid control action is prematurely terminated, potentially causing adverse consequences.

4) Determine How Potentially Inadequate Control Actions Could Manifest in the System and Develop Mitigations. In this final step, the analysis team explores how the identified inadequate control actions could manifest within the system. They also develop mitigations to address these vulnerabilities and improve system safety.” In step 3, one must consider the conditions below:

- Safety is compromised due to the absence of a necessary control action.
- A control action that is either incorrect or unsafe is implemented, resulting in a negative outcome.
- A control action that could be correct or sufficient is executed either too early, too late, or in the wrong order.
- A valid control action is prematurely terminated, leading to adverse consequences.

FRAM analysis involves four key steps, aimed at unravelling the intricacies of the system:

(1) Identifying and characterizing the functions of the system. Functions are the core activities, processes, and scenarios that contribute to the system's overall performance and outcomes.

(2) Recognizing and understanding the variability within the system. This step involves recognizing and understanding the variations, uncertainties, and deviations that can occur during the execution of functions within the system.

(3) Specifying how variability can be integrated into the analysis. In this step, the analysis specifies how variability can be integrated into the assessment, allowing for a deeper understanding of the system's responses to different conditions and circumstances.

(4) Implementing improvements based on the insights gained from the FRAM application (Hollnagel, 2012).

In the FRAM model, a function is defined by six distinct aspects outlined below:

1. Time (T): The temporal aspects that influence how a function is carried out.
2. Input (I): An element (such as activities, materials, or documents) that is utilized or transformed by a function to generate an output. Inputs also establish connections to preceding functions.
3. Output (O): The outcome of performing a function that establishes links to subsequent functions.
4. Precondition (P): System conditions that must be fulfilled before a function can be executed.
5. Control (C): A mechanism or process that coordinates or supervises the execution of a function to achieve the desired output. This can include plans, methods, procedures, instructions, rules, algorithms, etc.
6. Resources (execution conditions) (R): The necessary conditions or resources required for the execution of a function.

Variability in FRAM could be

1. Technology

2. Human function
3. Organizational (Hollnagel, 2012)

The experiment (micro analysis) conducted with smart glasses is analyzed and the results regarding the time and quality of the assembly system alongside the macro analysis including organizational aspects of the system are presented in the next chapter.

CHAPTER 3

RESULTS

3.1 Learning curves

To be able to analyze the data from the steady point, we calculated the learning curves for each participant and for each scenario. As shown in figure 3.1 for manual ratchet without glasses, figure 3.2 for pneumatic ratchet without glasses, figure 3.3 for manual ratchet with glasses and figure 3.4 for pneumatic ratchet with glasses. We verified the steady point to be at the 7^{th} bracket. Finding the steady point in a learning curve is about understanding when the benefits of learning and efficiency improvements start to diminish, allowing for more accurate planning and performance evaluation in assembly processes.

All following analysis is done from the steady point onward. The Y-axis is time per bracket.

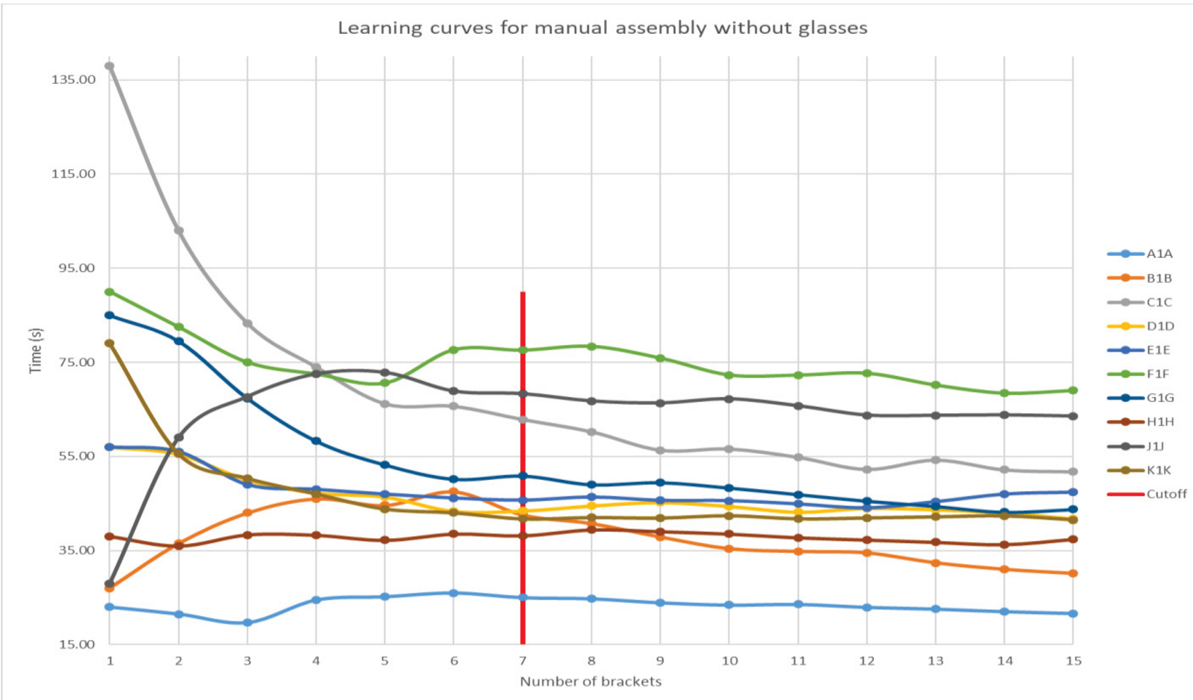

Figure 3.1 Learning curve and steady point for manual ratchet without glasses

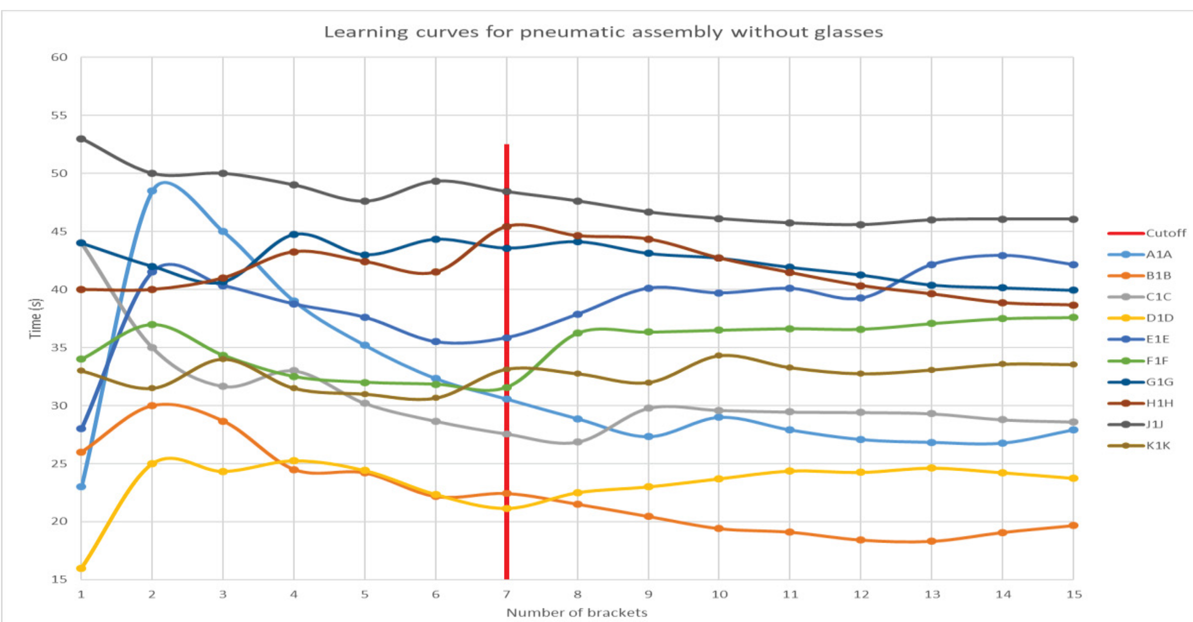

Figure 3.2 Learning curve and steady point for pneumatic ratchet without glasses

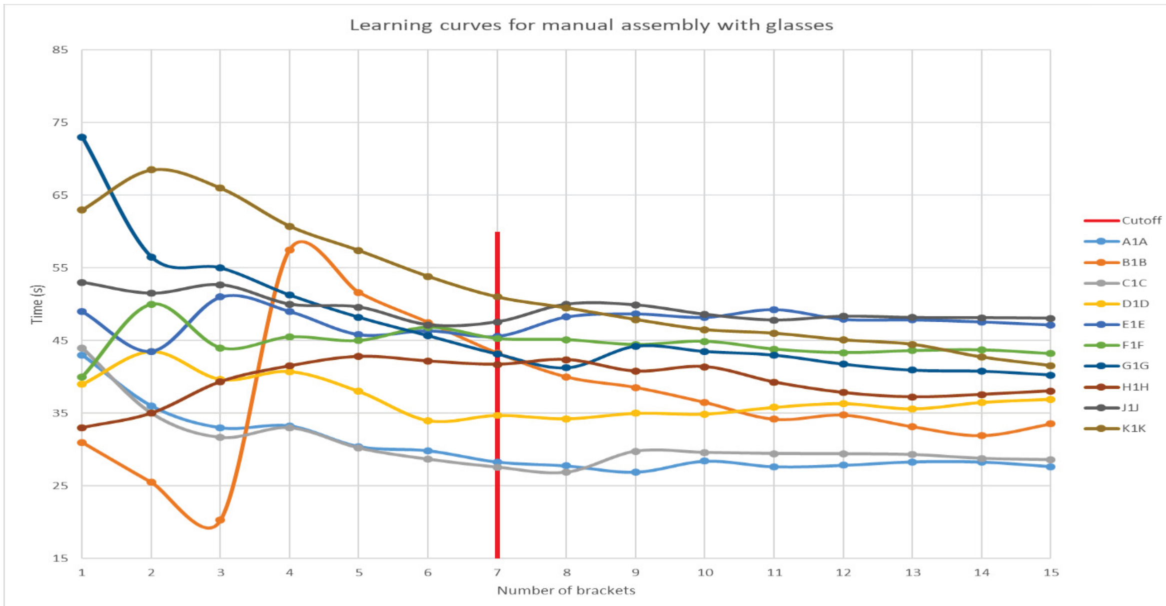

Figure 3.3 Learning curve and steady point for manual ratchet with glasses

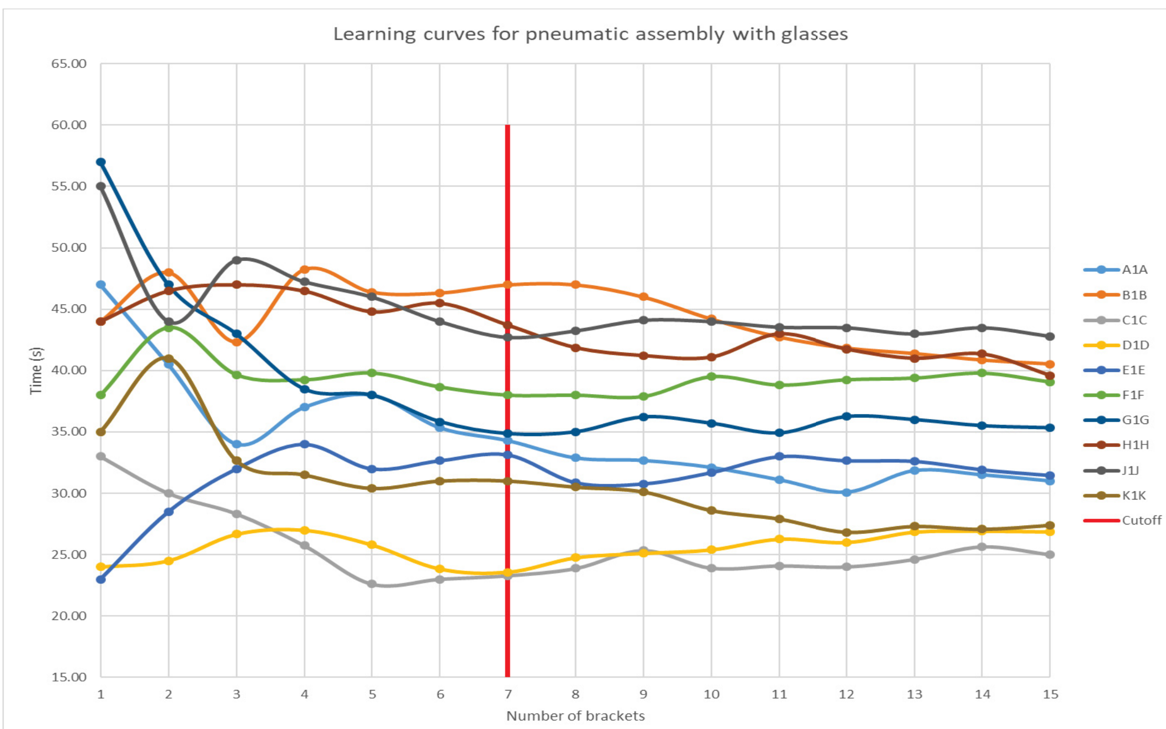

Figure 3.4 Learning curve and steady point for pneumatic ratchet with glasses

3.2 Impact of choice of tools

We analyzed the impact that different tools (manual and pneumatic ratchet) had on quality and time from the steady point for all 10 participants with and without glasses. See figure 3.5 and 3.6 for time comparison. Each assembly bracket from 7 to 15 is shown with a different color.

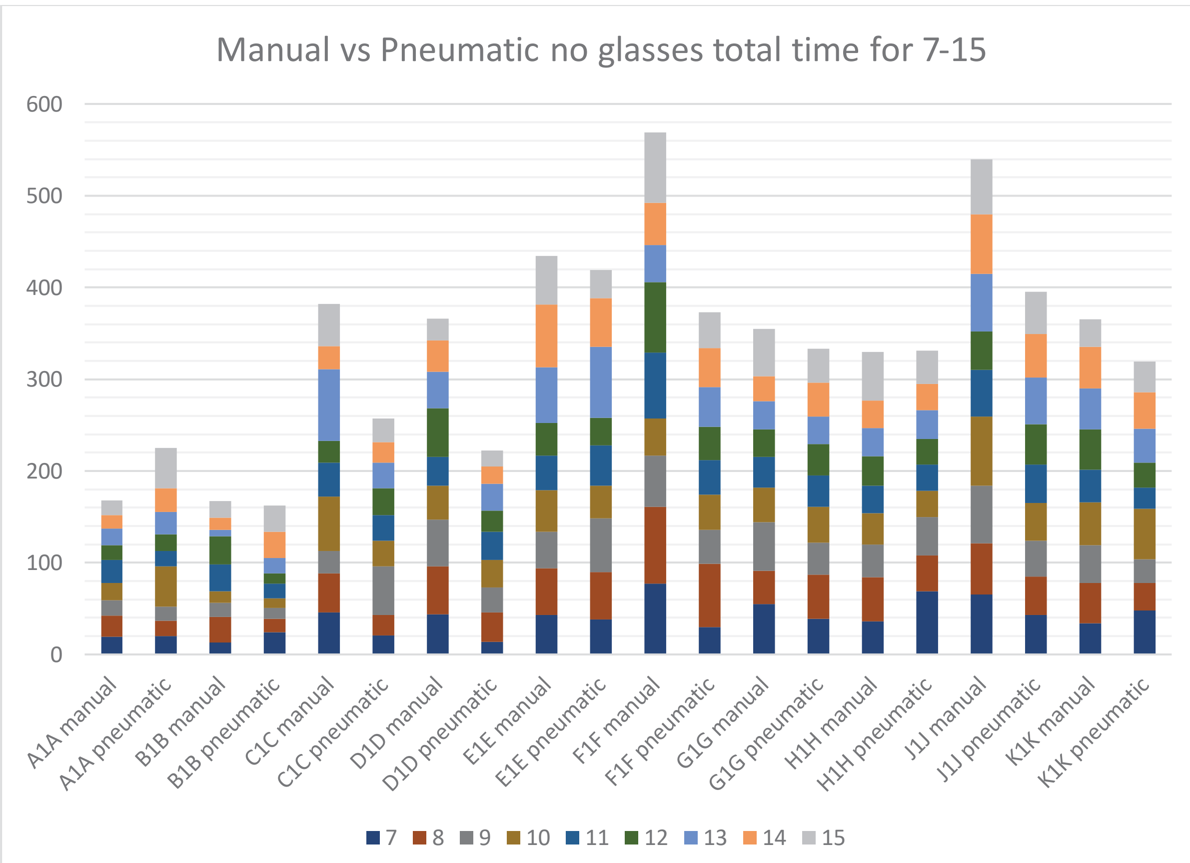

Figure 3.5 Total time (seconds) from the steady point for manual and pneumatic tool for 10 participants without glasses

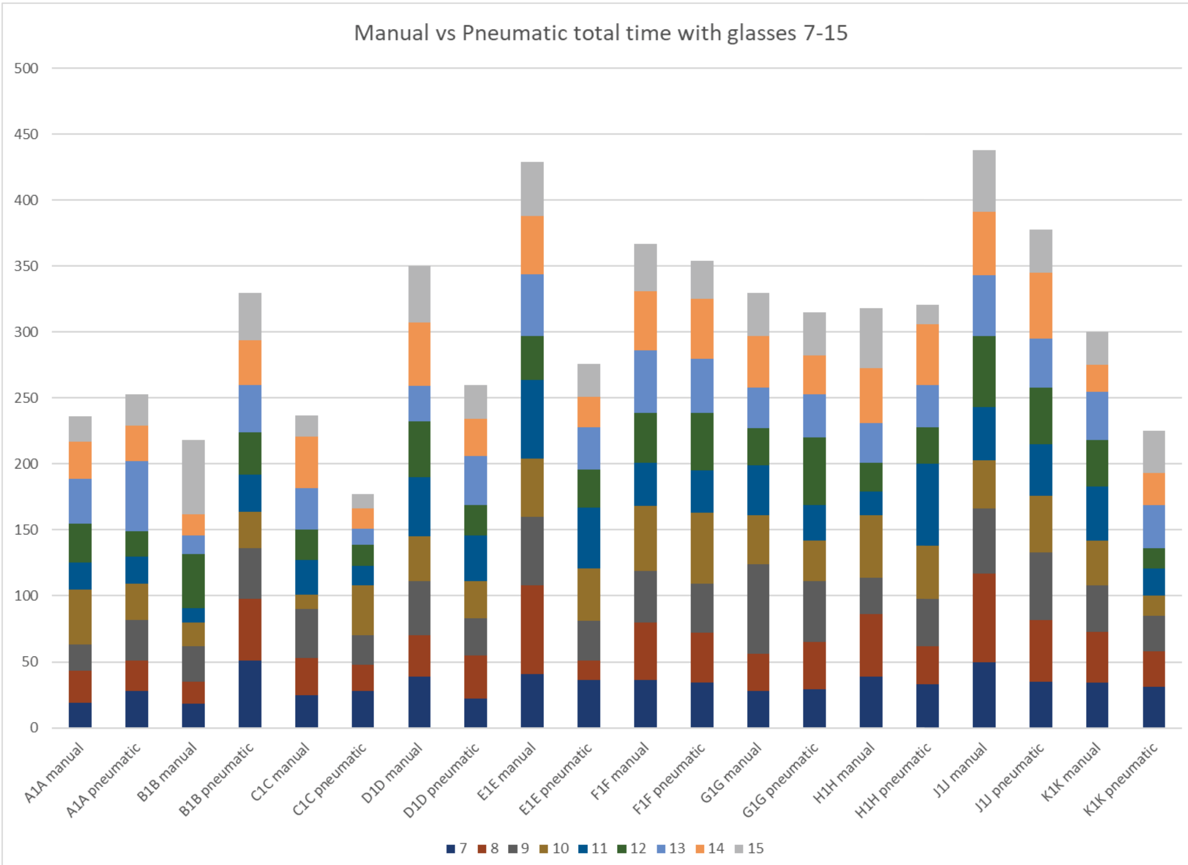

Figure 3.6 Total time (seconds) from the steady point for manual and pneumatic tool for 10 participants with glasses

Mean and standard deviation globally for time of each scenario is presented in Table 3.1. Scenario 1 to scenario4 present the four scenarios (scenarios) of the experiment. Scenario 1 manual ratchet without glasses, scenario 2 pneumatic ratchet without glasses, scenario 3 manual ractchet with glasses and scenario 4 pneumatic ratchet with glasses.

Table 3.1 Means and Standard Deviations for time (seconds) of each scenario globaly

	Mean	SD
Scenario 1 - manual ratchet without glasses	**40.84**	**17.45**
Scenario 2 - pneumatic ratchet without glasses	**33.73**	**12.91**
Scenario 3 - manual ractchet with glasses	**35.81**	**12.30**
Scenario 4 - pneumatic ratchet with glasses	**32.1**	**10.39**

Table 3.2 and Table 3.3 present the quality comparisons with number of participants who made a specific error with and without smart glasses.

Table 3.2 Number of participants who made each error without glasses

	Manual ratchet	Pneumatic ratchet
Loose bolts	**0**	**3**
Missed bin instruction	**6**	**6**
Missed alignment intruction	**5**	**6**

Table 3.3 Number of participants who made each error with glasses

	Manual ratchet	Pneumatic ratchet
Loose bolts	**0**	**5**
Missed bin instruction	**6**	**6**
Missed alignment intruction	**3**	**4**

Paired t-test:

Quality

- With p-value of 0.68, choice of tools had no significant impact on alignment mistakes without the usage of smart glasses.
- With p-value of 0.77, choice of tools had no significant impact on alignment mistakes after introduction of smart glasses.

Time

- With p value of 0.01, choice of tools had a significant impact on time without the usage of smart glasses.
- With p value of 0.17, choice of tools had no significant impact on time after introduction of smart glasses.

3.3 Quality

The quality of the finished scenario was assessed by verifying the alignments of installed brackets and the tightness of bolts for each participant. The brackets were expected to be aligned with the top and bottom of the plate they were installed on.

Some participants did not read the instructions completely, leading to missing details such as aligning the brackets and picking up the bolt box from the conveyor (Figure 3.7). Results show that slightly more participants had loose bolts with glasses while missed alignment instruction was seen more from participants without glasses and missed bin instructions was the same with and without glasses (Figure 3.7). However, these results were not significant. Three out of ten participants left bolts loose, and seven out of ten were unable to align the brackets properly.

With glasses some participants reported that they did not pay attention to the instructions on the smart glasses due to the repetitiveness of the scenarios. Five out of ten participants left bolts loose. Six out of ten were not able to align the brackets properly either due to lack of attention to instructions or difficulty handling the air ratchet as some reported. Moreover, three participants complained about the small or unclear text in the glasses as there was not any option for zooming in while using the glasses. Figure 3.7 illustrates a comparison for missed instructions (bin and alignment) as well as bolt loosness before and after glasses. Alignment mistakes are also presented in figure 3.8. Table 3.5 also shows the Means and STD for all four scenarios globaly.

Means and Standard Deviations for the alignment errors are presented in Table 3.2.

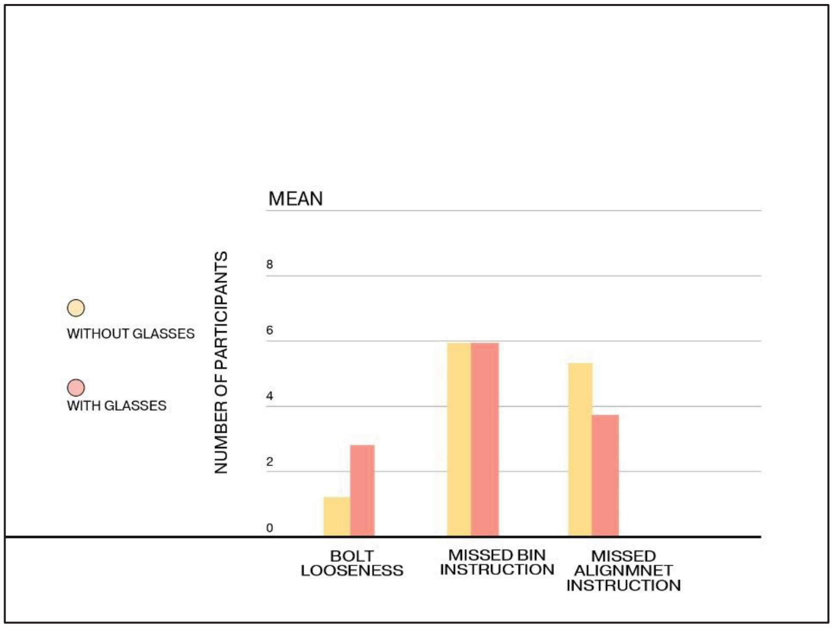

Figure 3.7 Mean for the number of participants who made errors with and without glasses

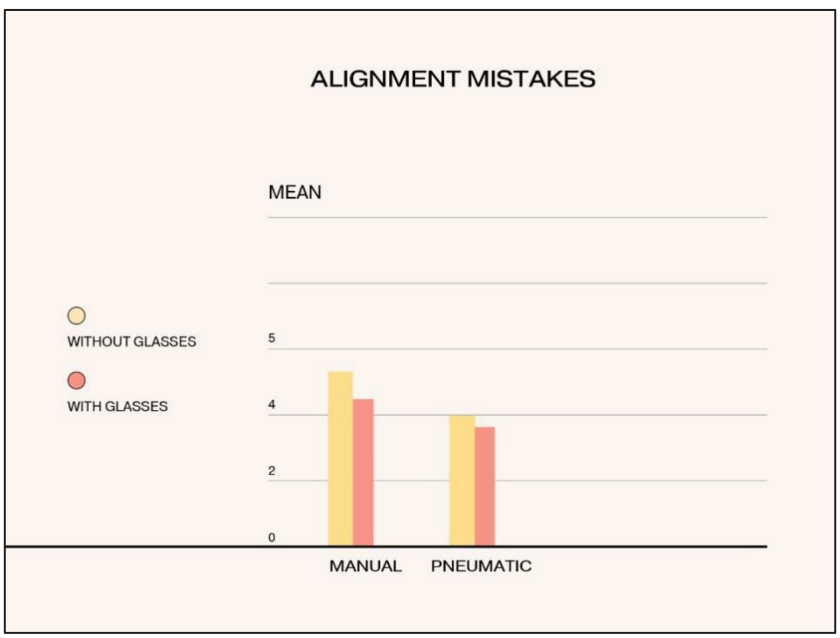

Figure 3.8 Alignment errors (mean) with different tools with and without smart glasses

Impact of Smart glasses on alignment mistakes

- With p-value of 0.48, introduction of smart glasses had no significant impact on alignment mistakes when using manual ratchet tool.

- With p-value of 0.54, introduction of smart glasses had no significant impact on alignment mistakes when using pneumatic ratchet tool.

3.4 Completion times

The experiment as a whole had an average completion time of 125.4 minutes with a standard deviation of 12.49. Results from the steady point show a mean of 40.84 seconds for manual ratchet scenario without glasses which is higher than pneumatic ratchet without glasses with a mean of 33.73. And the mean is also slightly higher for manual ratchet compared to pneumatic ratchet with glasses, with means of 35.81 for manual ratchet and 32.1 for pneumatic ratchet. It needs to be noted that some participants reported that they did not fully read the instructions on the glasses, as they were the same as previous scenarios, so they skipped them. Total time comparison for different tools with and without smart glasses is presented in Figure 3.9 and 3.10.

Means and standard deviations for each scenario is calculated (Table 3.4).

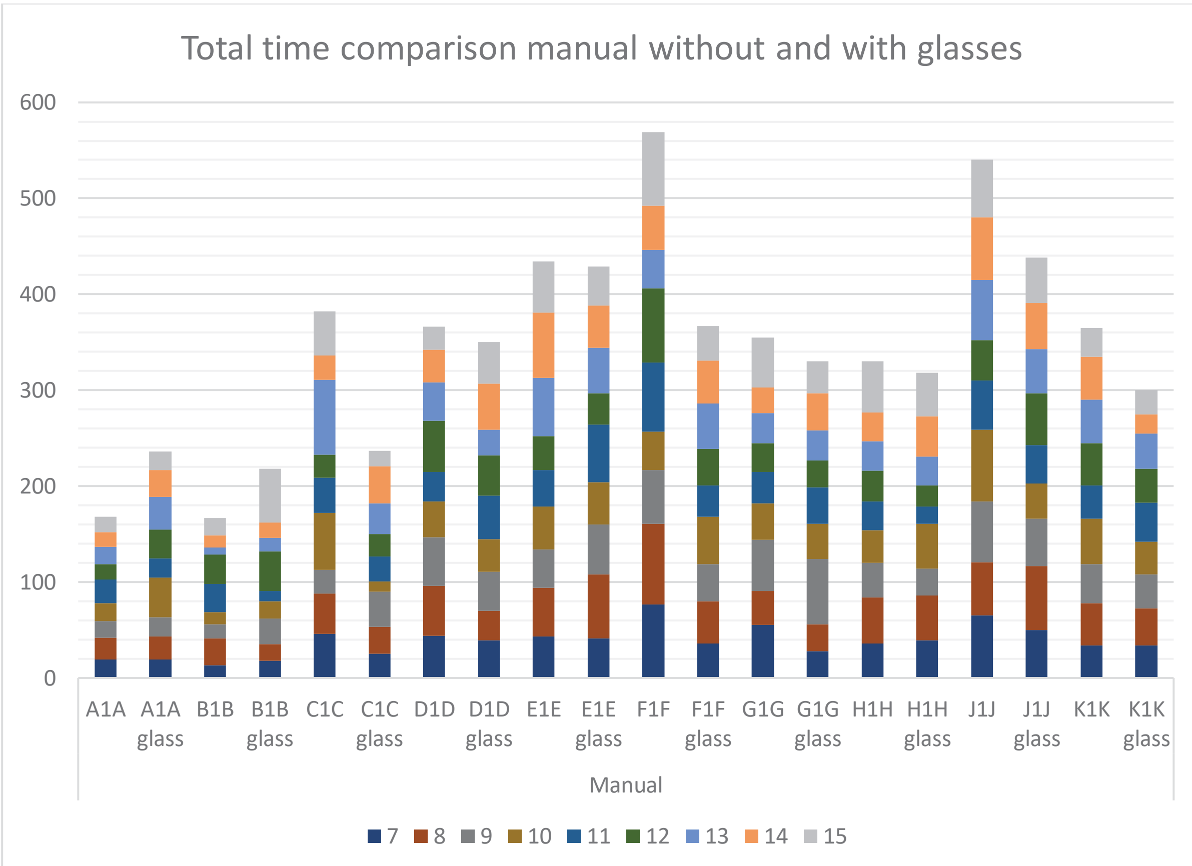

Figure 3.9 Time comparison (seconds) with and without glasses with manual ratchet

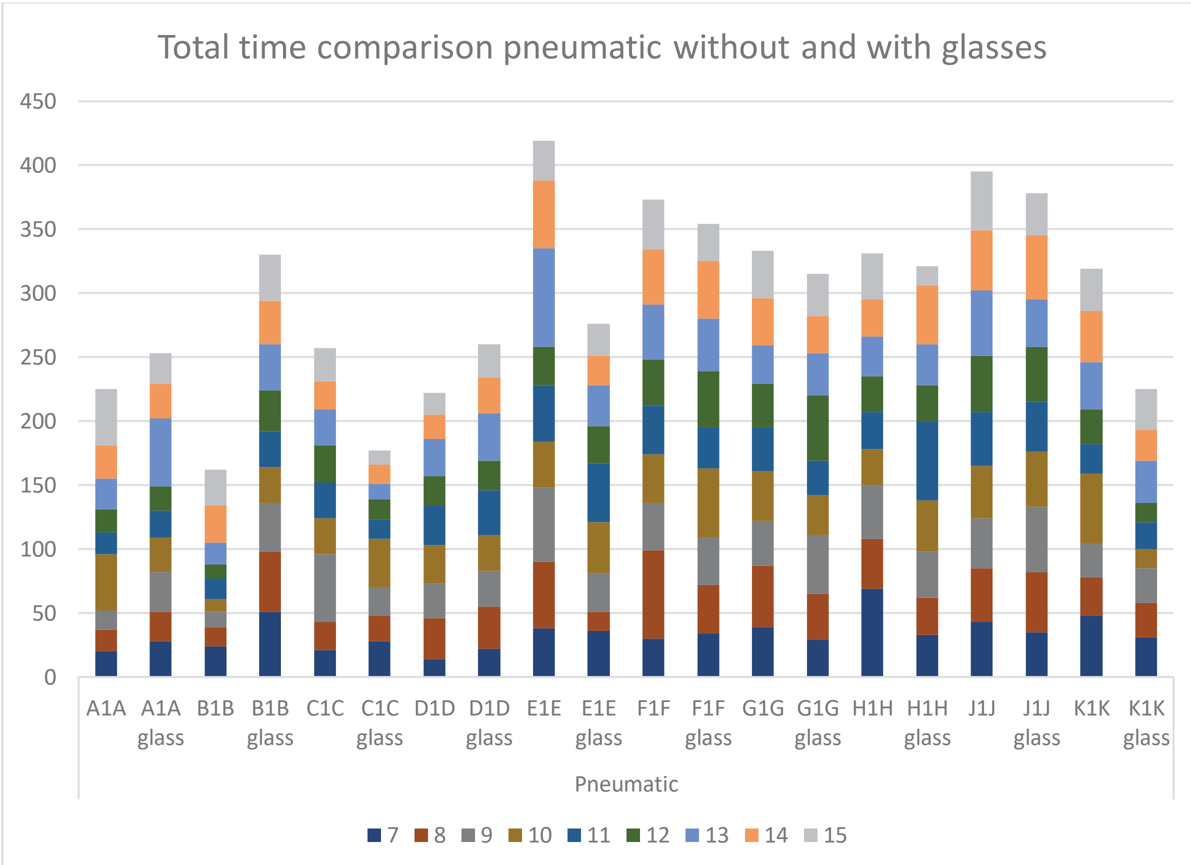

Figure 3.10 Time comparison (seconds) with and without glasses with pneumatic tool

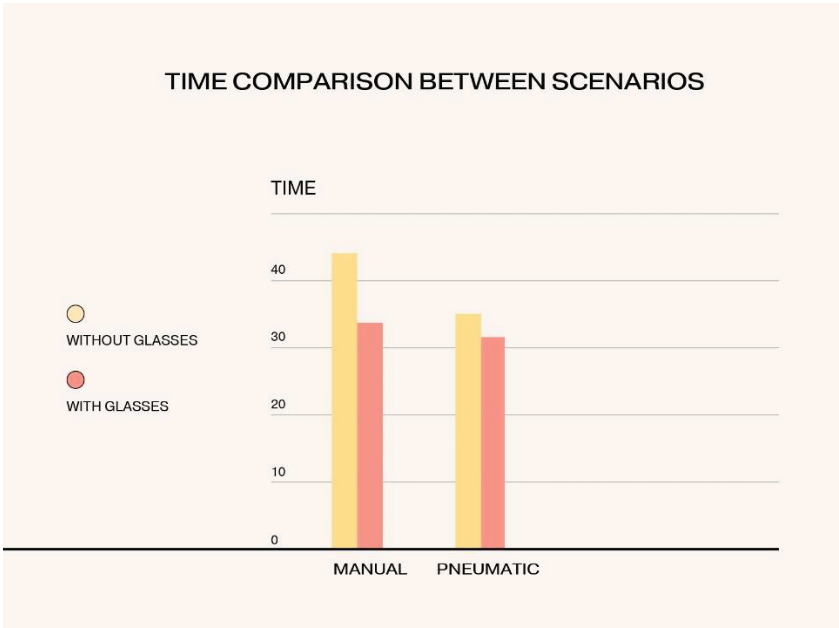

Figure 3.11 Average time (s) comparison for the four scenarios

Table 3.4 Means and standard deviations for time (seconds) for each participant and scenario from the steady point

A1A	**MEAN**	**SD**		**F1F**	**MEAN**	**SD**
T1	18.6	3.16		**T1**	63.2	16.68
T2	25	10.67		**T2**	41.4	10.40
T3	26.22	7.55		**T3**	40.7	5.28
T4	28.11	9.46		**T4**	39.3	7.29
B1B	**MEAN**	**SD**		**G1G**	**MEAN**	**SD**
T1	18.5	8.11		**T1**	39.4	10.29
T2	18	6.83		**T2**	37	4.71
T3	24.2	14.04		**T3**	36.6	11.33
T4	36.6	7.40		**T4**	35	7.73

C1C	MEAN	SD		H1H	MEAN	SD
T1	42.4	16.80		T1	36.6	7.78
T2	28.5	9.11		T2	36.7	12.38
T3	26.3	8.58		T3	35.3	10.45
T4	19.6	8.17		T4	35.6	12.33
D1D	MEAN	SD		J1J	MEAN	SD
T1	40.6	9.59		T1	60	8.90
T2	24.6	6.27		T2	43.8	3.41
T3	38.8	6.48		T3	48.6	8.08
T4	28.8	4.86		T4	42	6.11
E1E	MEAN	SD		K1K	MEAN	SD
T1	48.2	10.37		T1	40.5	5.67
T2	46.5	14.28		T2	35.4	10.07
T3	47.6	9.86		T3	33.3	6.30
T4	30.6	8.76		T4	25	6.44

Significance of results

- With p value of 0.12, introduction of smart glasses had no significant impact on time when using a manual ratchet tool.
- With p value of 0.59, introduction of smart glasses had no significant impact on time when using a pneumatic ratchet tool.

Table 3.5 presents the completion time Means and STD for the four scenarios

Table 3.5 Scenarios' alignment errors and completion time Means and STD

	Manual no glasses		Pneumatic no glasses		Manual with glasses		Pneumatic with glasses	
	Mean	**STD**	**Mean**	**STD**	**Mean**	**STD**	**Mean**	**STD**
Alignment error (number)	**4.70**	**2.41**	**4.30**	**3.13**	**4**	**2.54**	**3.90**	**3.31**
Time (S)	**40.84**	**17.45**	**33.73**	**12.91**	**35.81**	**12.30**	**32.1**	**10.39**

3.5 Assembly patterns used by participants

The pattern used by each participant to assemble 15 brackets in each scenarios was monitored to see if introduction of smart glasses would make a change.

- Some participants assembled groups of brackets (2 to 15) using 2-3 bolts to tighten the bracket manually for preliminary positioning, and some assembled brackets one by one.
- Only two participants changed their assembly pattern when going from manual ratchet to air ratchet assembly.
- Only three participants changed their assembly pattern once the intelligent glasses are introduced.

3.6 Eye-Tracking results

Due to technical issues, only data from three of the participants was usable. Regardless, results are presented as an introduction to future research which would result in interesting findings to see how the usage of smart glasses is affecting the scenario time and also distractions.

From the results of the eye-tracker we gathered that the frequency of additional look up at instructions was 18% lower with smart glasses (Table 3.5). These results are for the total assembly and not from the steady point. This was done by analyzing the Go-Pro camera videos and the eye-tracker videos. It was seen that the only look up at instructions was for the placement of brackets and not any other instructions. This could be explained by how the instructions were given in different screens and even though the participants could move back and forth between screens by pressing buttons, the action was not seen to be happening when rechecking this fact through Go-Pro cameras.

Table 3.6 Look-up without and with Smart Glasses

Avg Look-up without Smart Glasses	Avg Look-up with Smart Glasses
18	15

3.2 Macro analysis (complex hybrid assembly system) using systemic analytical analysis

3.2.1 FRAM

FRAM (Functional Resonance Analysis Method) was utilized to assess the implementation of smart glasses in assembly processes, considering the interactions and dependencies among system functions, human activities, and environmental factors. The analysis went as follows:

The analysis commenced by outlining the core functions within the manufacturing system and their interconnected dependencies. Then extensive exploration was undertaken to uncover intricate interactions and interdependencies among the various functions within the system. It was identified that workers exhibit adaptability in gestures to effectively communicate with the smart glasses, showcasing a dynamic and adaptive aspect of the system. Furthermore, diverse performance variations were noted:

- Workers' experience levels contributing to differing assembly times and error rates.
- How external elements like distractions and environmental conditions impact the accuracy of workers in adhering to instructions.

A key concern arose from poor clarity in assembly instructions, elevating the likelihood of incorrect assembly or product defects. Moreover, strategies focused on resilience and adaptability were highlighted:

- Provision of comprehensive training programs to enhance workers' familiarity with the smart glasses and their functionalities.
- Implementation of feedback mechanisms to promptly capture and address issues related to gesture recognition and instruction clarity.

Instances of functional resonance were brought to light, illustrating how changes or disturbances in one sector of the system can reverberate and impact other functions. For instance, delays in conveyor-part delivery could lead to idle time for assemblers. The analysis unveiled dynamic dependencies among the smart glasses, the conveyor system, and the assembly personnel. The smart glasses' instructions influenced assemblers' actions, while conveyor timing and speed affected assembly efficiency. Challenges pertaining to human-machine interaction were identified, particularly concerning the simultaneous handling of parts from the conveyor while reading smart glasses instructions. Environmental factors emerged as influencing the system's performance, including ambient lighting affecting smart glasses' display readability and noise levels affecting communication. Opportunities for systemic enhancements were brought forth, ranging from optimizing smart glasses' interfaces and adjusting conveyor speed to introducing feedback mechanisms for superior process monitoring. Positive aspects encompassed workers' adaptability in gestures for communication and the presence of training programs to enhance smart glasses familiarity. Negative elements encompassed variable worker performance due to experience and environmental influences, alongside concerns about poor instruction clarity. Various factors, including environmental influences and distractions, were highlighted as contributors to incorrect assembly or decreased productivity. Output variabilities for each function is presented in Table 3.7.

To address potential synchronization problems, the role of a worker stationed by the conveyor was recognized:

- Ensuring smooth part delivery and timely assembly.
- Monitoring conveyor operations and addressing disruptions promptly.
- Facilitating real-time communication to prevent delays and address issues.

  The overarching significance of implementing resilience strategies was underscored, emphasizing their role in mitigating risks, enhancing performance, and prioritizing worker safety. Figure 3.12 presents the final model of the analysis.

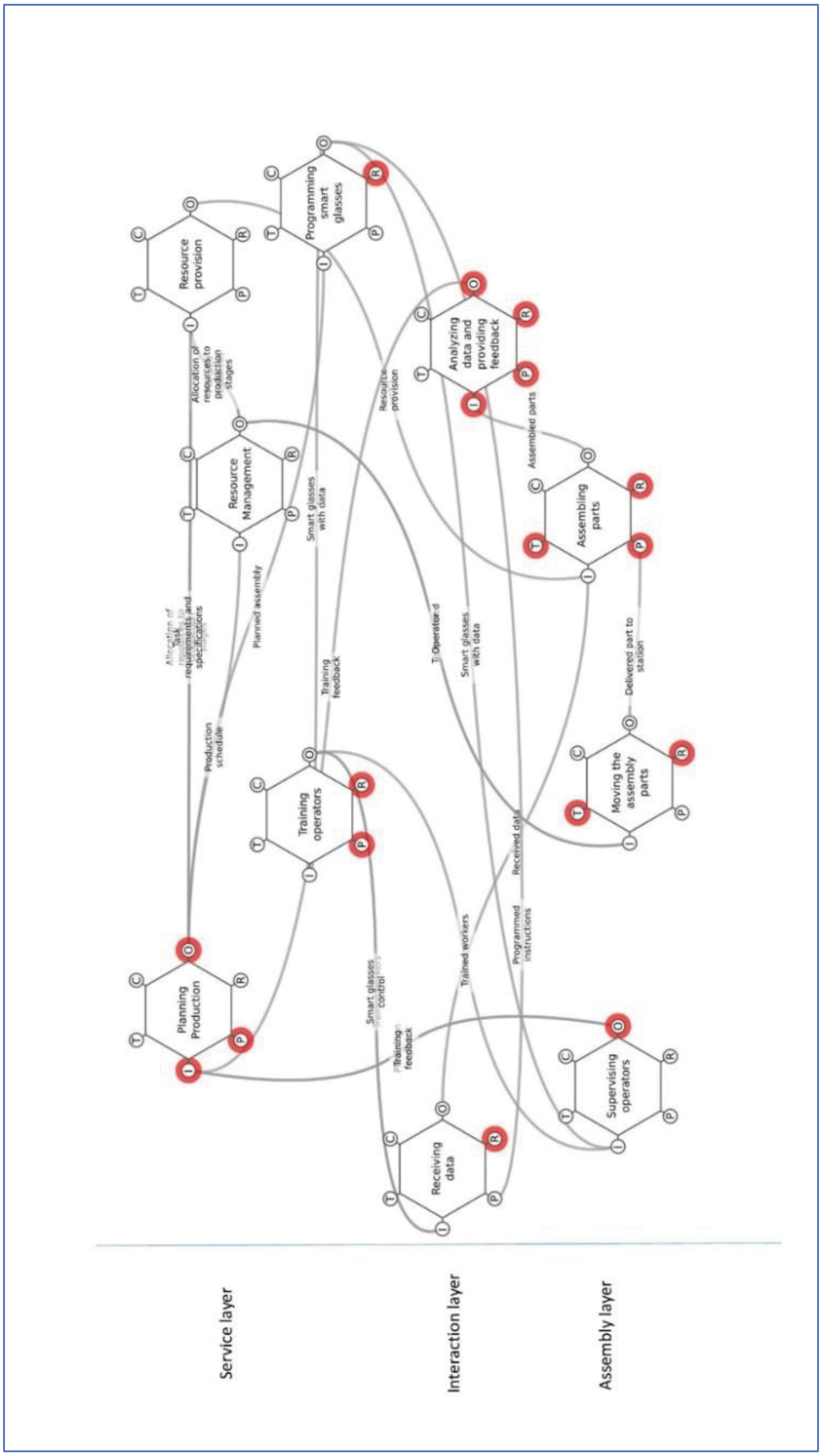

Figure 3.12 FRAM functions and connections

Table 3.7 Possible output variabilities

Function	Type of function	Output	Variabiliy
Programming Smart glasses	Technological	Programmed instructions for smart glasses	Different programming needed for different workers
Receiving data	Technological	Received data for processing	Imprecise and late- the received data is sent late or imprecisely.
Analyzing data and providing feedback	Technological	Rate of usage of materials	Imprecise and late- the provided result is late or imprecise.
		Feedback related to productivity, workers' performance, overall quality of assembly line	Imprecise and late- the feedback is provided late or is imprecise.
		Result of the analysis of the speed of workers	Imprecise and late- the provided result is late or imprecise.
Moving the assembly parts	Technological	Part delivered to station	Late/too early – speed of the conveyor is slower/faster than expected.
Supervising workers	Human	Supervisor feedback for training programs	Imprecise – feedback might be imprecise and not provide appropriate information for the training department.

Function	Type of function	Output	Variabiliy
Training operators	Organizational	Trained workers	Imprecise – if the training process is not performed properly, or due to internal variabilities, such as ineffective communication.
Resource Management	Organizational	Resource provision plan	Imprecise or late – the plan of resource provision might have been prepared imprecisely or late.
		Other organizational department feedback	Imprecise or late – the provided feedback might be imprecise or late.
Providing Resources	Organizational	Resource provision	Imprecise or late/too early – the resource might be provided imprecisely or late/too early.
Planning Production	Organizational	Assembly planning	Imprecise – the provided plan might be incomplete, or may contain incorrect information.
		Supply demands	Imprecise or late – supply demands might be provided late or be imprecise.
Assembling parts	Human	Assembled parts	Imprecise or late – the connector could be assembled late or imprecisely by the worker.

3.2.2 STAMP-STPA

STAMP-STPA analysis are explained below and the overview of the studied system can be found in Figure 3.14 and 3.15.

Top-Level Hazard: An incorrect assembly or defective product due to errors or malfunctions associated with the use of smart glasses.

Control Structure: The control structure includes the smart glasses themselves, the assembly process, the assembly workers, the software or applications running on the smart glasses, and any external systems or interfaces.

Loss Scenarios: Possible loss scenarios include misinterpretation of assembly instructions displayed on the smart glasses, software or hardware failures in the smart glasses, distractions caused by the smart glasses, or inadequate training on the proper use of the smart glasses. The analysis identified that the design of the smart glasses ensures a degree of isolation from the programming, workstation, and other system components. This design choice contributes to reducing the risk of unintended interference or manipulation from external sources.

Unsafe Control Actions: Unsafe control actions include assembly workers following incorrect or misleading instructions displayed on the smart glasses, workers becoming overly reliant on the smart glasses without verifying critical information independently, or workers neglecting other safety considerations while wearing the smart glasses.

Causal Factors: Causal factors contributing to the unsafe control actions involve issues such as unclear or ambiguous instructions displayed on the smart glasses, software bugs or glitches, lack of proper training on smart glasses usage, distractions caused by the augmented reality features of the smart glasses, or inadequate integration of the smart glasses with existing assembly processes. Notably, the absence of direct connections between production planning, resource management, resource provision, and the workstation or the programming of the connected glasses can have certain implications. Potential effects include discrepancies between the planned resources and the actual usage, delays in resource allocation due to lack of real-time data exchange, and challenges in adapting production plans based on the assembly progress captured by the smart glasses. Additionally, the inability to synchronize these functions with the workstation might hinder efficient resource utilization and responsiveness to dynamic changes. The system's one-way connection from the workstation to the assembly, focused on training and monitoring by the supervisor, introduces potential synchronization problems and usage difficulties. As there's no real-time feedback or interaction from assembly workers to the supervisor, issues such as delays in conveying problems, lack of immediate assistance, and inability to address real-time concerns could arise. This unidirectional communication might lead to misunderstandings, hinder troubleshooting, and delay error rectification.

Analysis of Control Actions and Causal Factors: It was discovered that the integration between the smart glasses and the network is prone to occasional errors, leading to disconnections and loss of instructions and therefore delay in assembly.

Safety Constraints and Recommendations: Based on the analysis, safety constraints and recommendations include improving the clarity and accuracy of assembly instructions displayed on the smart glasses, implementing rigorous testing and quality control processes for the smart glasses and associated software/network, providing comprehensive training programs for assembly workers to ensure proper usage and understanding of the smart glasses, and establishing protocols to address distractions or potential over-reliance on the smart glasses, and exploring ways to enable more interactive and two-way communication between workstation and supervisors. By conducting an STPA analysis in the context of using smart glasses in assembly processes, organizations can proactively identify potential hazards, understand their underlying causes, and implement necessary measures to enhance the safety and reliability of their operations.

Figure 3.13 and Figure 3.14, illustrate the hierarchical structure of the complex hybrid assembly line. The first two figures show the different subsystems and components of the assembly line, including the integration of smart connected glasses into the workflow. These figures help to identify and understand the interactions between system components and the integration of the smart connected glasses, providing a visual representation of the factors that contribute to the overall impacts of using smart connected glasses in the assembly line. Figure

3.14 illustrates how smart connected glasses are integrated and how they affect the overall workflow and efficiency of the workstation.

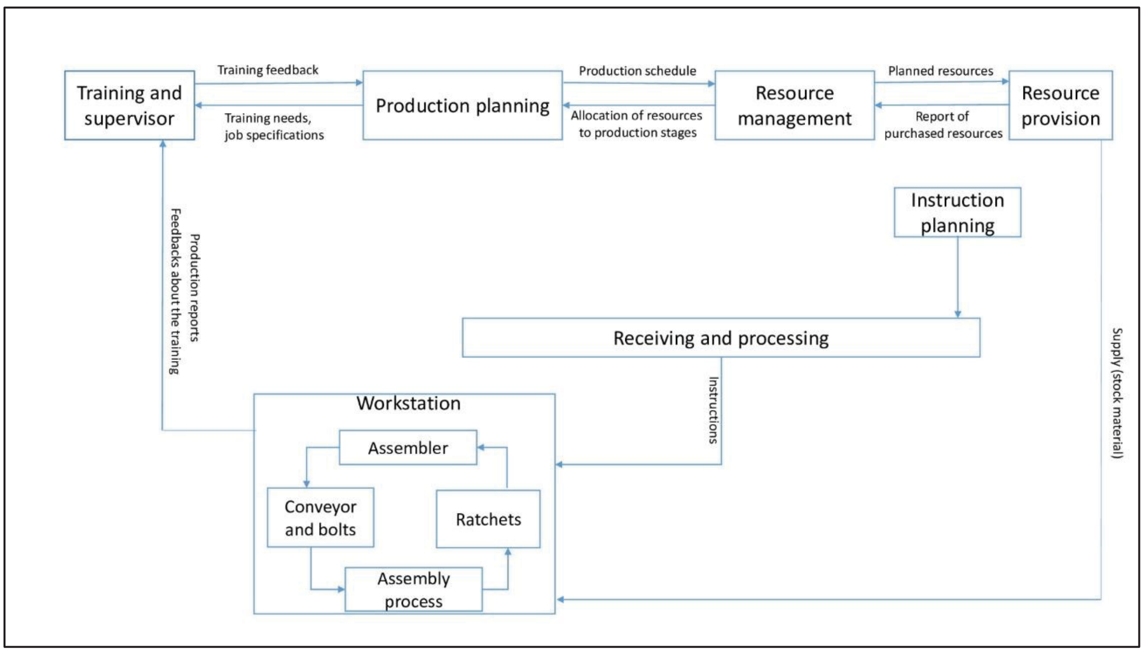

Figure 3.13 STPA without smart connected glasses

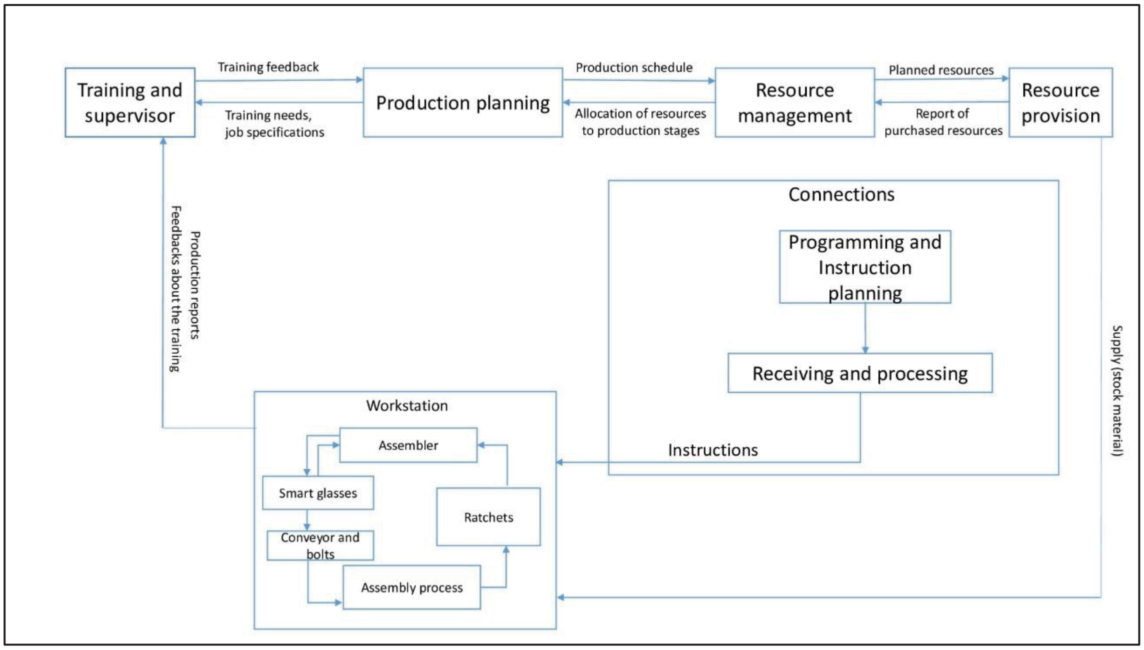

Figure 3.14 STPA with smart connected glasses

CHAPTER 4

Discussion

4.1 Micro-analysis (workstation)

In this study, we calculated the leaning curves and identified the steady point to be at the 7th bracket and all analysis was done from that point.

4.1.1 Impact of choice of tools

As results show in this experiment, the choice of tools has a significant impact on the scenario time when doing the assembly without intelligent glasses, but not on quality which partially rejects the first hypothesis "Choice of tools has a significant impact on quality and time". The literature posits that the choice of tools highly affects the error rate (Camillo, 2010). This study also suggests that error proof tools, that use sensors to control the amount of force, could be used to have less error rate in assembly when using torques. This is due to the fact that use of tools such as torques create more impulse force resulting in placement errors (Ay et al., 2017). In our study, no torque control was used which could have impacted the results. Also, the added complexity with introduction of smart glasses could explain why there was no significant results with the glasses.

4.1.2 Quality

As for the quality of work, in this experiment the hypothesis "Usage of smart glasses significantly increases quality of work." is rejected. Our results do not show a significant impact on quality. Results are contrary to the results of others such as Dorloh and Li, (2023). These authors compared a Hololens 2 AR smart glass, video display, and paper instructions in assembly-disassembly of a computer. Results showed that the usage of AR had lower error rates compared to other methods. In our study, we are not using fully the AR functionnalities of the glasses as our experiment used the glasses in a connected way. The glasses sent visual instructions step by step to the participants only, without a feedback loop with other elements of the workstation. In other studies such as Chiew et al., (2021) AR glasses and a mix of 3D models and text are used for instructions and speech recognition for the assembly of a laptop. AR functionalities, as well as how instructions are delivered to participants, seem to have a significant impact according to the literature.

In our study, results showed bolt looseness to be slightly higher with glasses and missed alignments were slightly lower with glasses but more data would be needed. Moreover, alignment errors were slightly less with glasses with no significancy. Based on the calculated means and standard deviations, it is gathered that manual scenarios generally had slightly higher error rates than pneumatic scenarios. Also, the use of glasses seemed to have a more consistent impact on pneumatic scenarios in terms of error rate variability.

4.1.3 Time

We also observed that the use of smart connected glasses did not result in shorter completion times for assembly scenarios with any significant results, which is not consistent with the literature (Żywicki and Buń, 2021; Bartuska et al., 2022; Theis et al., 2015). Theis et al. (2015) used a monocular smart eyewear Liteye LE 750A to do manufacturing tasks on a car engine and carburettor and checked the worker performance. They found that it took more time to complete the manufacturing tasks with the smart glasses studied. Żywicki and Buń's (2021) study was focused on the Moverio BT-300 and Vuzix MT-300 glasses functions and how to use these augmented reality glasses for tasks such as picking parts in an assembly workstation. Bartuska et al.'s (2022) study used augmented reality with the use of a ViewSonic Pro8800WUL DLP projection system to provide wall building assembly instructions. They also found that it was shorter to complete the assemblies with the AR system. "The direct comparison of study results requires consideration of different hardware, tasks and contexts" (Theis et al., 2015), as well as how the instructions are delivered and presented to the participants. In our study participants are completing a complex assembly task involving a cognitive and perceptual (visual and tactile) effort. Instructions are also delivered similarly without and with smart glasses.

Eventhough the selection of participants was not based on experience, some participants had experience with assembly and the tools which resulted in shorter completion times for them. Also, some participants had difficulties to put in the bolts due to crossthreading specially towards the end of their experimental session (scenario 2 and 3) which resulted in longer completion times and could partly explain how no improvement was seen in scenario time after introduction of glasses. We also calculated the standard deviation which is a measure of the variability or spread of the data. Larger standard deviations indicate greater variability in the data points. In our case, the scenario with manual ratchet and without smart glasses shows greater variability while the scenario with pneumatic ratchet and with smart glasses indicates less variability in the assembly time.

To gain a deeper understanding of the impacts of smart connected glasses on scenario time, we used eye tracking. Although the eye tracker data was limited, it provides interesting insights into look-up times, highlighting the need for further investigation in future studies.

Research suggests that assembly instructions matters. Blasing et al. (2021) argue that the solution to preventing issues that come from complexity of assembly instructions lies not in reducing complexity, but in improving the way instructions are

presented, to reduce the effort required to find necessary information. Wickens et al. (2008) found that a combination of auditory and visual instructions yields better results than relying solely on one input type. The presence of performance difficulty and errors is associated with the presentation of a large amount of information (Kumar & Lee, 2022) and the method used to present information in complex scenarios, which affects the cognitive load and the effort needed to understand the given information (Mittelstädt et al., 2015). It could be useful to highlight the parts of instructions which are essential, but might be overlooked in the glasses.

Another difference between the results of this study and part of literature could be due to the fact that the experiment was designed to be more similar to real assembly in manufacturing and actual manufacturing tools were used instead of toys as in (Yuan et al., 2008; Ceruti et al., 2017; Laun et al., 2022a). Moreover, in studies using toys, the complexity of the system affects the final results as well as the model of the smart glasses being used (Laun et al., 2022a). The level of information details is also demonstrated to be of great impact on the quality of an assembly (Stockinger et al., 2023).

4.2 Macro-analysis (complex hybrid assembly system) using systemic analytical analysis

Analytical modelling methods such as the Functional Resonance Analysis Method (FRAM) and Systems-Theoretic Process Analysis (STAMP-STPA) were employed to study the integration of smart devices in complex hybrid assembly systems.

4.2.1 FRAM

FRAM highlighted worker adaptability, but also variable performance and clarity concerns. Functional resonance instances also showcased ripple effects from disruptions. Furthermore, existence of a worker by the conveyor was identified to manage synchronization and disruptions, ensuring real-time communication. We established that the lack of seamless links between production planning, resource allocation, and the actual workstations or connected glasses can lead to several consequences. Furthermore, the inability to coordinate these processes with the workstation can impede resource efficiency and the ability to adapt to changing circumstances.

4.2.2 STAMP-STPA

STPA’s focus on causal analysis and safety-oriented approach helps identify systemic factors contributing to failures and guides improvements for enhanced system reliability. STPA revealed a top hazard of incorrect assembly due to smart glasses errors. Loss scenarios included misinterpretation and software failures. Unsafe actions involved overreliance on smart glasses and neglecting safety. Causes included unclear instructions, software glitches, and poor integration. A lack of direct connections affected resource planning and adaptation. Moreover, unidirectional communication caused synchronization and usage challenges.

Cognitive stress factors can be categorized into two groups: the complexity of parts to be assembled and the complexity of the smart workstation itself (Ansari et al., 2020). The challenges stemming from system complexity significantly impact the realization of sustainable operations, particularly those related to human-centred factors (Ngoc et al., 2021; Moencks et al., 2021). Recognizing the role of humans in the workstation, as well as the overall assembly system, and prioritizing their needs are essential to addressing these challenges (Grandi et al., 2019).

4.3 Biases and limitations

The study was limited by the small number of participants and the use of only one smart glass model (Vuzix M400), which has a battery life of only one hour. Further studies should explore other assembly scenarios, including those in which a supervisor provides verbal instructions, and where multiple smart wearables are used. Also, the jig height was the same for all participants, which may have been the cause of unusual postures in one of the individuals (see annex V).

The research question of this study was focused on understanding the impacts of using smart glasses on complex hybrid assembly lines. In addressing this question, we conducted an in-depth investigation (micro-macro) to examine various aspects related to the use of smart connected glasses in complex hybrid assembly systems.

Our study contributes to the advancement of integrating smart glasses, more precisely, connected glasses, in complex hybrid assembly systems. The contribution is more focused on the micro-macro impacts of smart glasses than only on their sole usability aspect, which is less present in the literature.

Furthermore, our findings highlight the need to carefully manage the visual complexity in assembly instructions and improve the delivery of information to reduce the effort required for comprehension. The impacts of system complexity on the cognitive load and the challenges associated with realizing sustainable operations in human-centred workstation are also highlighted. By acknowledging the role of humans in the design and prioritizing their needs, we can address the implications of system complexity in terms of time, quality and human factors.

Overall, this study provides valuable insights into the effects of smart connected glasses on assembly scenarios, informing the development and optimization of smart technologies.

Future research should continue exploring the eye tracking data and further investigate the impacts of smart connected glasses on different aspects of scenario performance, as well as investigate additional factors that may influence the effectiveness of smart connected glasses in various industrial settings. Smart glasses, if used to their full potential, could take advantage of virtual reality technologies to send feedback and real-time data to the production planning, supervisor and related departments, as the STPA and FRAM results show.

CONCLUSION

This thesis embarked on a comprehensive exploration of the impacts of integrating smart glasses in a connective way into complex hybrid assembly lines, all within the context of Industry 5.0, which underscores the seamless collaboration between humans and machines. The literature review revealed that while manual work remains indispensable, the transition to semi-manual workstation, often facilitated by smart wearables like smart glasses, is gaining momentum. Challenges such as user acceptance and ergonomic considerations were identified, while advantages including reduced training time were evident. Striking a balance between functionality and wearability at an affordable cost remains a challenge for widespread adoption.

The experimental investigation (micro analysis – workstation) conducted in this research project shed light on the practical implications of smart wearables, particularly smart glasses, within the manufacturing domain. A laboratory experimental design with ethical approval was employed, involving 10 participants who engaged in assembly scenarios using various tools, including smart glasses. The findings revealed that the introduction of smart glasses led to no significant change in quality and scenario completion time. However, choice of tools showed a significant result in scenario time.

Furthermore, the study adopted systemic analysis (macro analysis) models like STAMP-STPA and FRAM to provide a holistic understanding of the complex assembly system in a connected manner. STAMP-STPA focused on safety hazards and failures, analyzing control structures and information flow, while FRAM offered a broader perspective, considering interactions and dependencies, including positive aspects. FRAM results showed that the implementation of smart glasses in assembly processes revealed a dynamic system with worker adaptability in gestures but variable performance influenced by experience and environmental factors. Poor instruction clarity raised concerns about incorrect assembly. The importance of resilience strategies, including comprehensive training and feedback mechanisms, was emphasized to mitigate risks and enhance worker safety. The STPA analysis of implementing smart glasses in assembly processes identified a top-level hazard of incorrect assembly or defective products linked to smart glasses errors or malfunctions. Unsafe control actions were attributed to issues like unclear instructions, software glitches, and one-way communication, potentially leading to synchronization problems and delayed error rectification. To enhance safety, recommendations include improving instruction clarity, rigorous testing, comprehensive worker training, and exploring two-way communication, emphasizing the importance of proactive hazard identification and safety measures in smart glasses integration.

This research contributes valuable insights into the integration of smart wearables, facilitating decision-makers in optimizing production processes and ensuring the occupational health and safety of workers.

The scientific contribution in this research is the fact that we looked into the micro-macro impacts of introducing smart glasses in a connected way in the workstation alone and in a bigger scale, in the whole system including organizational aspects as well. In essence, this thesis underscores the multifaceted nature of smart wearables in Industry 5.0, highlighting their potential benefits in terms of effectiveness and efficiency, while also acknowledging the challenges related to user adaptation and system complexity. The findings emphasize the need for continuous refinement in smart wearables' design, clear instructional interfaces, and robust training programs.

Recommendations for Future Research

To further advance the understanding of smart wearables in complex hybrid assembly environments, future research should consider the following areas:

1. **Usability and Interface Design**: Delve deeper into the design aspects of smart glasses interfaces to enhance usability and reduce user errors.
2. **Long-term Adoption and User Acceptance**: Conduct longitudinal studies to assess long-term adoption and understand user dynamics over time.
3. **Enhanced Training Strategies**: Develop and evaluate advanced training programs to address the learning curve associated with smart glasses.
4. **Integration with Existing Systems**: Explore seamless integration with existing production systems, considering interoperability and efficiency.
5. **Worker Health and Ergonomics**: Investigate the long-term physical and psychological effects of prolonged smart glasses usage to ensure worker well-being.
6. **Interactions in complex hybrid systems**: Study interactions between human workers, smart glasses, and other automated components within complex hybrid assembly lines.

As we navigate the transformative landscape of Industry 5.0, smart glasses and similar technologies emerge as powerful tools that bridge the gap between human expertise and machine precision. This thesis represents a vital step in unveiling the intricate dynamics of these technologies within complex assembly environments. It reaffirms the potential for smart wearables to enhance productivity and worker satisfaction while recognizing the challenges inherent in their adoption.

In the ever-evolving manufacturing sector, this research serves as a beacon of insight, guiding us toward a future where technology and humanity coalesce seamlessly. The journey towards Industry 5.0 is a collective endeavor, and the lessons derived here contribute to this ongoing exploration. With careful consideration of design, training, and safety, smart glasses will continue to shape a manufacturing landscape that is not only efficient but also responsive to the needs and well-being of its workforce.

In closing, this thesis encapsulates the essence of progress, where innovation and practicality converge. Smart glasses, like the generations of technology before them, become catalysts for change, advancing the industry and enriching the lives of those who propel it forward.

ANNEX I

DISSEMINATION

Journal articles to be written and submitted post-thesis defence

Conference Articles and posters

1- Published

- 2023 Khodammohammadi, N., Ngô, V.T.M., Nadeau, S. Integrating Smart Glasses in a Hybrid Manufacturing System: Towards a Better Understanding of Impacts on Productivity, Quality and Ergonomics/Human Factors. CIGI-QUALITA-MOSIM 2023, June 14-16 2023, Trois-Rivières, Canada.
- 2022 Khoddammohammadi, N., Nadeau, S. Integration of traditional, automatized and intelligent technologies in manufacturing: Towards the integration of smart glasses. CARWH Conference, Poster, September 15-16 2022, Remote, Canada.

ANNEX II

CONFERENCE PRESENTATION

INTEGRATING SMART GLASSES IN A HYBRID MANUFACTURING SYSTEM: TOWARDS A BETTER UNDERSTANDING OF IMPACTS ON PRODUCTIVITY, QUALITY AND ERGONOMICS/HUMAN FACTORS

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Presented in CIGI QUALITA MOSIM 2023

Abstract

Production process is progressively shifting away from fully automated towards hybrid alternatives. Technology-assisted manual labor in manufacturing, more specifically low-volume processes, promises increased job productivity and is expected to support the workers. This study aims to gain a better understanding of the impacts on productivity, quality and ergonomics/human factors, when smart glasses are introduced in a hybrid system.

10 recruited participants were asked to do four complex assemblies each with 15 repetitions using manual and air ratchets with and without smart glasses. The data was collected through cameras, an eye-tracker, time measuring, NASA-TLX for scenario workload and quality control with documented pictures of each finished assembly.

Results show that completion time was shorter with the smart glasses and, with assembly repetition, participants skipped reading some instructions. Globally, the weighted and unweighted NASA-TLX were high for the physical and effort indicators. Participants' individual scores however show important differences. All participants

made assembly errors, whether bracket alignment or loose bolts. The tools used (manual and air ratchet) had an impact on quality.

This paper presents preliminary results. More refined analysis of this study's data is needed to better comprehend how to integrate conventional, automated, and intelligent technology like smart glasses.

Keywords: intelligent wearables, smart glasses, assembly systems, manual assembly.

1. Introduction

1.1 State of the art

Intelligent wearables have a wide range of potential applications (e.g. aircraft maintenance with speech recognition) (Siyaev and Jo, 2019; Chen et al., 2019), according to research. But compared to conventional, completely manual procedures, semi-manual assemblies could lead to an increase in complexity (Naeini and Nadeau, 2022). Researchers have shown that the widespread industry use of intelligent technology will cause the use of intelligent wearables to rapidly increase (Dimitropoulos et al., 2021). Additionally, flexible human-computer interaction, such as intelligent wearables, can offer greater user experiences in comparison to conventional rigid and heavy interactive equipment (Yin et al., 2020).

More precisely, wearables gather information from their surroundings, conduct essential data processing and output the processed data, as well as operate as a component of a larger smart system (Fernández-Caramés and Fraga-Lamas, 2018). Wearables can be used to assist humans in, for example, monitoring work situations, activities and processes (Pokorni and Constantinescu, 2021) and in this way, can support occupational health and safety (OHS). Among others, they can provide timely alarms and crucial visual information for assembly, improvement and conformance verification, helping thus to reduce human errors (Torres et al., 2021; Nadeau et al., 2022). Making sure wearables are accepted and used correctly in real work situations is a crucial component of practice, as for any tool or system (Nielsen, 1993). It is imperative to make sure any technology is user-friendly and useful (e.g necessary to enter a site or operate a specific equipment) (Barata and Cunha, 2019) before being put into operation.

Smart glasses are wearable devices with multiple sensors, an embedded processor, and a digital display for viewing and interaction. For example, to assemble a product, workers can receive instructions, taken from an assembly database through smart glasses. In this way, workers can easily adapt to different product types, and the training time of employees to assemble new product types is reduced (Torkul et al., 2022). The main challenges with smart glasses are hand and eye coordination with complex scenarios

(Kreutzfeldt et al., 2019), the need to balance performances with usability measures for scenarios requiring more movement (Chua et al., 2016), higher accuracy and device's cybersecurity when use of gesture is integrated in the smart glasses (Yi et al., 2016). It has been identified that when the hands are occupied, receiving information through smart glasses does not lead to an increase of scenario performance (Theis et al., 2015). Computer Vision Syndrome (Blehm et al., 2005) could be observed after prolonged use. Ongoing use of eye-sensitive technology has been found to have an impact on users' brain and eyes (Mann, 2013). These challenges have been studied and are still studied in the literature and we invite the readers to consult the review of Nadeau et al. (2022) on that behalf.

1.2 Research contribution and perspective

Understanding how industry can use intelligent wearables in hybrid systems, specifically smart glasses, and their impacts on operational aspects (time and quality) and on ergonomics/human factors is the objective of this study. In this study we employed an experimental method to better understand the practicality of smart glasses. The data process is then explained and the results are demonstrated. In the end we discuss our findings and compare with the available studies and give our suggestions for future work. User experience has been considered in the study to conclude the relationship between user perception of the work and comfort and the efficiency of the assembly done. It is in our objectives to conclude the efficiency of smart glasses in the aspect of human-machine interaction and point out the challenges these technologies face.

2. Methods

2.1 Experimental process

A laboratory experimental research was chosen for this study. The protocol was approved by the Ethical Committee of École de technologie supérieure in July 2022. This type of experiment was chosen for the lack of practicality in the models used in the literature. This way we could have a better understanding of the use cases of smart glasses. Limitations of this experiment include the number of participants that we were being able to recruit and specific model of the glasses used in the experiment.

10 individuals participated in the study, aged between 22 and 51 years old, from the academic environment and outside of academic environment regardless of experience. An equal chance of participation was given to both genders when recruiting and the study was carried out with equal numbers of both genders. Participants were recruited through ads on campus and were invited to attend an information meeting. Participants interested completed a consent form and the 2022 Par-Q+/2022Q-AAP+ questionnaire. Data was gathered during a two-week timeline in autumn 2022.

The tools used in the scenarios were a manual ratchet and an air ratchet (Figure II.1). Participants were asked to assemble L-shaped brackets with bolts with and without wearing smart glasses in an ergonomic standing posture (adjustment of the jig's height). More precisely, four distinct scenarios were designed:

1. manual ratchet without Vuzix M400 glass;
2. air ratchet without Vuzix M400 glass;
3. manual ratchet with Vuzix M400 glass;
4. air ratchet with Vuzix M400 glass.

All scenarios had the same scenarios, with the same assembly and brackets configurations. They consisted of 15 repetitions, each requiring about a minute to complete. A 10 minutes break was provided to the participants in between each scenario. The participants were not given any time limits in the study.

All the bolts were delivered to them at once, at the start of each scenario, in a box, on a conveyor near the assembly jig illustrated in (Figure II.2). Before beginning with each participant, a brief tutorial on how to use the tools and components was provided. The participants had to select the appropriate bolts between the two types provided based on the instructions. For the first two scenarios, both the instructions and an image of the final assembly were printed on paper and attached to the jig above the plate they needed to work on. For the third and fourth scenario, the same instructions and image of the final assembly were only provided in smart glasses. During all scenarios, participants were filmed for upper limb movements with 2 GoPro Hero 3+ cameras which were located on the jig on both sides of the participant, and the time was measured with a chronometer and confirmed by the cameras. A Pupil-labs core eyetracker was also used to track eye movements.

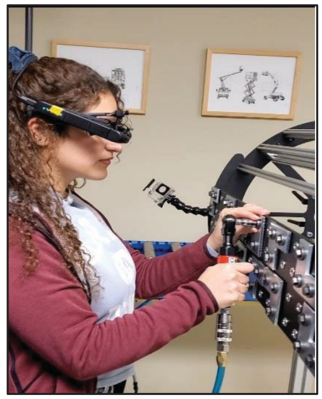


Figure A.II.1 Assembly of brackets on a simulated plane engine using smart glasses

Each participant completed a NASA-TLX survey at the end of the experiment which assessed the subjective workload experienced while doing scenarios. Also, each participant's specific comment on the scenarios and usage of smart glasses were documented.

2.2 Data processing

In this paper, preliminary experimental results were obtained by analysis of:

1. the time indicator collected with the chronometer and the Go-Pro Hero 3+ cameras, checking the time difference usage of smart glasses brings

2. the subjective assessment of the workload using the NASA-TLX scoring worksheet; analysing the workload participants felt overall.

3. the error/quality indicator with documented pictures and tightness check of each bolt of the finished assembly after each scenario. Getting an understanding of how smart glasses would affect the quality aspect of the assembly.

Figure A.II.2 Assembly jig designed at ETS

3. Results

3.1 Completion times

The total experiment took on average 125.4 minutes with a standard deviation of 12.49 to complete. The total scenario completion time was shorter (mean 35.4 minutes, STD 6.63 without glasses; mean 33.6 minutes, STD 6.72 with glasses) when using the smart glasses and participants were less likely to go back to read instructions repeatedly. Results in Table II.1 show the completion times for each assembly scenario. Some participants stated that they were not fully reading instructions on the glasses, since the steps were the same as previous scenarios, they simply skipped them.

Table A.II.1 Scenarios' completion times

Average time (minutes)	STD (minutes)		
Without glasses	Manual ratchet	19.4	4.73
	Air ratchet	16.1	4.54
With glasses	Manual ratchet	19	4.07
	Air ratchet	14.6	3.13

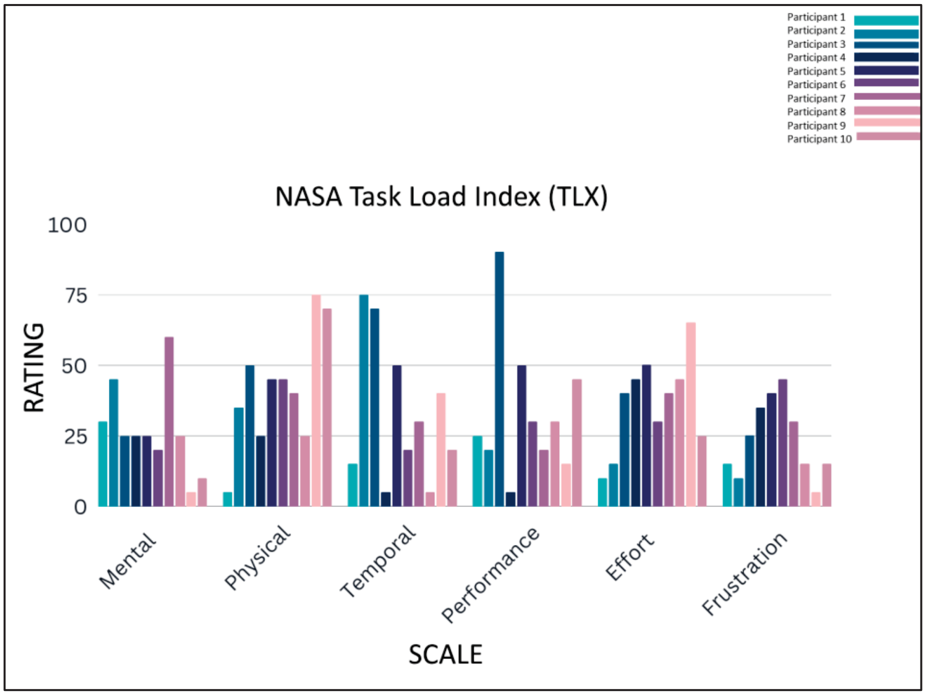
3.2 NASA-TLX

Results of the weighted and unweighted NASA-TLX in Table II.1 demonstrate that, globally, participants were feeling more physical demand and effort than mental demand and frustration from the scenarios. However, individually, (Figure A.II.3) shows that subjective results vary between participants.

Table A.II.2 Weighted and raw global NASA-TLX

Group Score Results			
Weighted		**Raw/Unweighted**	
Overall	35.67	**Overall**	25.00
Diagnostic Subscores		Diagnostic Subscores	
Mental	75.00	Mental	27.00
Physical	137.22	Physical	41.50
Temporal	73.13	Temporal	33.00
Performance	99.50	Performance	33.00
Effort	108.50	Effort	36.50
Frustration	85.63	Frustration	23.50

Figure A.II.3 Individual NASA-TLX scores for the 10 participants of the study



3.3 Quality

Quality of the finished scenario was documented for each participant by checking alignments of installed brackets and the tightness of the bolts. The brackets were supposed to be aligned with the top and bottom of the plate that they were being installed on.

Without glasses:

1. None of the participants completed the assemblies without any mistakes. 9 out of 10 participants did not read instructions completely, resulting in missing details such as aligning the brackets and picking up the bolts' box from the conveyor.
2. 3 out of 10 had left bolts loose.
3. 7 out of 10 were not able to align the bracket properly.

With glasses:

1. None of the participants completed the assemblies without any mistakes. Some participants stated that they were not paying attention to the instructions on the smart glasses because of the repetitiveness of the scenarios.

2. 5 out of 10 had left bolts loose.

3. 6 out of 10 were not able to align the bracket properly either due to lack of attention to instructions or difficulty handling the air ratchet as they testified.

4. 3 participants complained that the text in the glasses was small or unclear.

4. Discussion and conclusion

As the use of smart glasses was introduced after two times of doing the same scenario without the glasses, the presence of a learning curve must be taken in consideration and will be calculated and presented in a subsequent paper. The impact of this learning curve might explain partly why the completion times of the scenarios with the smart glasses are shorter.

A substantial amount of data provided on a device for human-machine interaction leads to visual complexity, which increases the user's cognitive load (Kiangala and Wang, 2019). This could increase fatigue and decrease user's attention (Tsutsumi et al., 2020). Furthermore, two cognitive stress factors have been reported for users: complexity of product parts and complexity of the environment (Ansari et al., 2020). Eye tracking measurements and upper limbs movements will be analyzed in a subsequent paper. This analysis should objectify changes of strategies in reading instructions with repetitions and differences in eye movements in scenarios with and without smart glasses as well as might explain partly individual NASA-TLX differences.

The tools seem to have an impact on the alignment and bolt looseness quality indicators with and without smart glasses. It seems easier to control and hold the brackets when using a manual ratchet. Most participants were able to align brackets better with it. Bolts were left loose more when the air ratchet was used which could be a result of the hand not feeling the tightness as much as when using a manual ratchet.

It needs to be noted that the model of glasses is important in a study and the results of this study are only based on one model (Vuzix M400 smart glasses) with specific characteristics. As the NASA-TLX survey was given to the participants at the end of their participation session and was based on the whole work done, the results cannot be used as an interpretation of the differences between scenarios with and without smart glasses. Also, due to the design and production method of the jig used, cross-threading of some nuts were problematic and made it hard for participants to tighten some bolts. Repairs were done between participant's experiments. No testing of the participants' eyesight was done before experiments, some participants expressed concerns and slight eyesight difficulties. For participants already wearing prescription glasses, the smart glasses were attached to a cap. Moreover, battery life is a critical matter in using smart glasses. The model used in this study was able to perform for around one hour for the specific input. A battery charging station and back-up batteries were available.

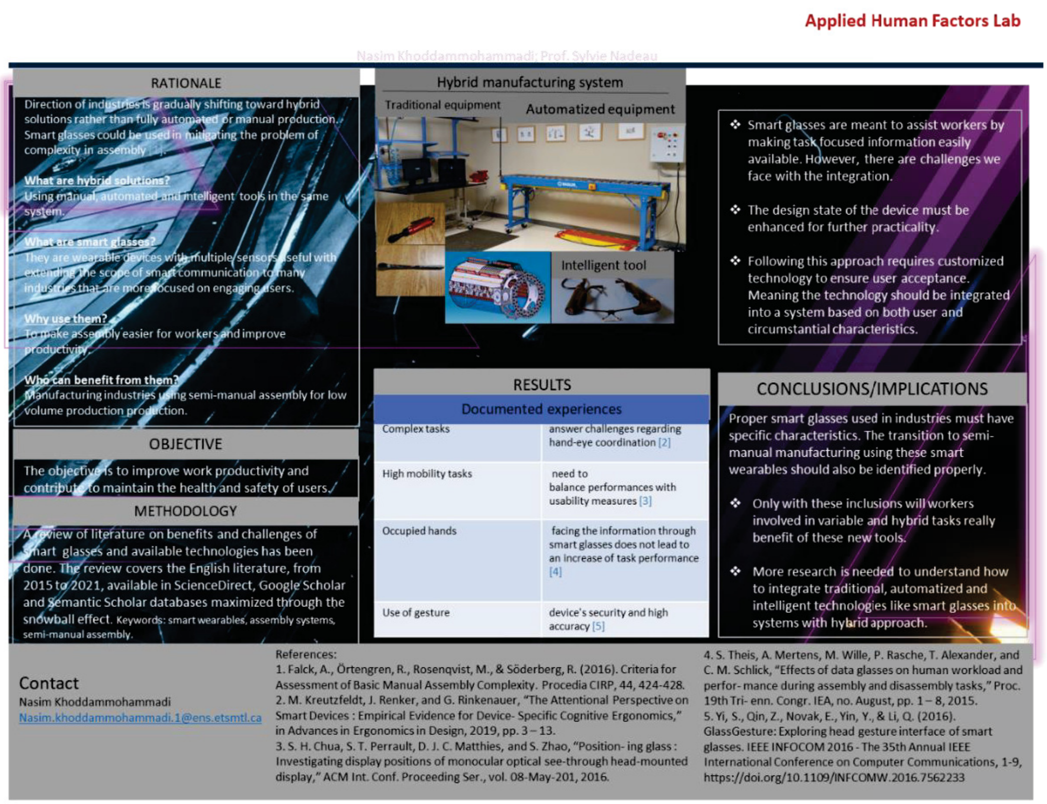
Smart device's usability and usefulness both have tremendous value for industrial deployment and integration in hybrid manufacturing systems. Further studies should explore other assembly scenarios, including scenarios where a supervisor delivers verbal instructions/support and scenarios integrating more than one intelligent wearable.

5. Acknowledgments

The authors acknowledge the funding and support of École de technologie supérieure (ÉTS) as well as the Natural Sciences and Engineering Research Council of Canada (NSERC). They would also wish to acknowledge the networking activities enabled by the Smart-Digital and Green Innovation Network (SDG Innovation Network) as well as the Intelligent Cyber Value Chain Network (CEOS Net).

ANNEX III

CARWH CONFERENCE, POSTER



ANNEX IV

REVIEW OF LITERATURE ON OTHER SMART WEARABLES

Smart Gloves

The usage of sensory gloves has been investigated for a wide range of uses, as: hand posture monitoring, computer-generated (typically virtual reality or augmented vision) environments and many others. Different sensors may be included in these instrumented gloves, such as microphones, proximity sensors, force sensors, flexion (bend) sensors, accelerometers (ACCs), gyroscopes. Furthermore, because mobility is a natural component of these systems, they are wireless devices with limited computational capacity and energy autonomy governed by the batteries they can carry (Cerro et al., 2021). It is needless to say that for enhancing the interaction with virtual and extended reality systems (XR), the user's hands need to be unoccupied. Also, there needs to be a haptic report and a technique for assimilating gestures so that the experience is even closer to reality (Johnson-Glenberg, 2018). Therefore, approaches in which the user is given a controller are not assessed as realistic (Bowman et al., 2012). Haptic interactions are in a way to give a touch sensation by vibration, heat, force, motion to the user (Kumar and Lee, 2022). A research done in 2017 illustrated how haptic interactions can furthermore engage the user in the XR systems (Kim et al., 2017). This shows the importance of intelligent gloves in manufacturing. Smart gloves could also be used to receive the output stream of the data flow whenever an error occurs (Funk et al., 2016). As far as the matter of errors and controlling goes, it is also found that haptic interactions are commonly used to control and monitor scenarios (Kumar and Lee, 2022).

Some studies have had ergonomic concerns while using smart gloves. In these studies, the capability of the glove to become a part of the user to increase comfort was not achieved (Sánchez et al., 2016; Aliyu and Almadani, 2018). Tracking forces exerted by workers could also be a reason for using smart gloves. In an approach that has a methodology where both the human and technological aspects are considered, various prototypes were utilised to test different ergonomic features. The first was developed to see where the components should be located; the second to select the sensor configuration; and the third to assess the performance and test the ergonomics of the glove. It should be considered, as recommended, to provide more directions when putting on and taking off the glove. Extra apertures were made in the glove to reduce moisture collection. Robustness was addressed by adding extra layers within the glove to alleviate the risk of shredding the glove. Even though the functional outcomes were adequate, they were insufficient to ensure good performance and complete user satisfaction. The results were that a human-factors-based methodology for determining the function of different prototypes along the process can be further refined (Francés et al., 2019).

Recently, with a macro-level ergonomic focus, the use of data gloves in assembly processes, as well as the associated occupational health and safety (OHS) and operational risks, was explored (Mofidi Naeini and Nadeau, 2022).

This was the first collaborative OHS and operational risks analysis on the use of a data glove in a system. The goal in this research was to demonstrate how using FRAM (a systematic model that analyses system activities) to analyze the potential risks associated with the use of a data glove in an assembly system can provide an accurate representation. To provide a better understanding of the subject while there is a limited knowledge related to the research topic, FRAM was applied to realistic case studies. The research demonstrated that FRAM is able to provide a proactive perspective for the analyst and systemic perspective of industry 5.0 concerning complexity of systems can be accomplished by the use of FRAM. For an overall understanding of a complex system a combination of FRAM and Systems Theoretic Process Analysis (STPA) has been introduced (Mofidi Neaini and Nadeau, 2023).

This approach gives a full detailed analysis of organizational functions. A very vivid perception of wearables is the fitting part which also applies to standard gloves. Harrabi, et al., (2008) studied the flexibility of a variety of protective gloves, to characterize the gloves stiffness as perceived by the users. A review of hardware, algorithms and application of data gloves while employing gesture recognition is done in 2023 by Pan et al.

Furthermore, a review of Human-Machine Interface in 2022 describes different methods of interacting with smart devices (Kumar and Lee, 2022). This study indicates that the design of these systems must be based on cognitive and physical perspective formulation. Overall, gesture recognition seems to be the most common interaction method in data gloves and risk analysis are offered for these complex systems to identify challenges.

In smart gloves, the important aspect is not only the way they fit the body part and hold tightly enough for a comfortable use but how they can adapt to different features in different individuals with different hand size for example that could need precise measurement for individuals. It needs to be taken into account that human bodies react differently to the temperature, humidity, the fabric or material that has been used in the wearable device and moreover, the pressure it will have on that body part. The researches done in this area raises some unanswered questions related to the operator rather than the productivity, as the focus appears to be more centered on the machines, devices and how they could be improved rather than having some focus on the user (Harrabi et al., 2008).

Exoskeletons

Exoskeletons are mechanical frameworks designed to be worn on the body with the goal or aiding the wearer's motions and scenarios by amplifying their strength or capabilities (de Looze et al., 2015). The first contemporary exoskeleton was created for industrial applications. General Electric created a full-body exoskeleton in 1965 to lift heavy loads. The challenges related to recognizing human motion intent, dealing with mechanical intricacies, handling data processing delays, and addressing the substantial mass (700 kg) have all hindered further advancements in this field (Makinson, 1971). As these intelligent wearables can improve operator comfort as well as performance, sectors that rely heavily on manual labour and are difficult to automate could profit tremendously from them. Exoskeletons offer a versatile alternative in situations where other solutions may not be suitable. As a result, testing procedures are currently under development for potential industrial adoption (Masood et al., 2018). By describing exoskeletons as wearable machines, designed to enhance the user's performance, exoskeletons could be characterized in two groups: active and passive. Active exoskeletons are defined to use a power supply of some kind, such as motors, hydraulics, or pneumatics, to operate the exoskeleton's parts in coordination with the user. Passive exoskeletons are those that employ non-powered options such as springs and dampers to assist the user's actions and posture. The capability offered by passive exoskeletons to sustain taxing positions for longer is how the performance improves. As for the Active type, the performance is improved by additional physical strength (Looze et al., 2016; FoX et al., 2019). Active exoskeletons have been found to give more flexibility and might be better suited to deliver more efficient support. Therefore, active devices might be more suited for demanding and complex jobs, including moving heavy objects (Toxiri et al., 2019).

The vast majority of available exoskeletons for industry are passive systems and the real-world applications of these solutions are on the rise (Amandels et al., 2018). Car industry has also started to put these devices into practice and test them (Hensel and Keil, 2019). Inclusively, strategies for improving industrial processes should consider the fact that wearing the same exoskeleton can make some scenarios easier while making others more challenging. As a result, wearing an exoskeleton cannot be anticipated to prompt an overall improvement in performance characteristics. Instead, improvements in some scenarios may be countered by poor performance in others (Baltrusch et al., 2018). Mechanisms related to users' acceptance or rejection of exoskeletons play a role in the system's overall performance and results of the system. A recent case study was carried out as an experiment with industrial logistics workers. The study revealed that exoskeleton testers' self-efficacy beliefs accelerated only under particular conditions, implying that industrial exoskeletons are not a technology to be used by just everyone.

To enhance user well-being and consequently improve performance, it is crucial to focus on tailoring the characteristics of work scenarios accordingly (Siedl and Mara, 2021).

In studies on exoskeletons, reliability of the findings is sometimes limited in lab tests because the active exoskeleton is only evaluated on a small number of participants (Looze et al., 2016).

Regarding use of exoskeletons for manual material handling, there has been no proof that using exoskeletons poses any particular hazards to the health and safety of the workers. On the other hand, it is highlighted that the exoskeleton is not helpful in dynamic jobs and is actually viewed as a disadvantage by workers. According to lab research as well, this factor makes it necessary to carefully choose the scenario for which the exoskeleton will be worn (Zhu et al., 2021). Because of the increased complexity of their scenarios in contrast to routine exercises, on-site research that investigated workers' experiences while using exoskeletons yielded results that were generally less remarkable than those observed in controlled laboratory tests. Exoskeletons are not a curative for employees or job scenarios; they often showcase a greater portion of their capabilities when engaged in stationary scenarios, but when it comes to dynamic roles, they tend to present a challenge in terms of regular job performance (Baldassarre et al., 2022).

ANNEX V

ANALYSIS OF UNUSUAL POSTURE

As per the one participant with unusual posture and their NASA-TLX survey, the physical demand is scored higher than mental. To analyze the posture we employed the Employee Assessment Worksheet (REBA) technique, which assesses every aspect of the human body, as it offers a comprehensive evaluation. The assessment of risk level is conducted manually through a scoring system as the means of data processing.

The data processing method is outlined as follows:

1. Assign a value to Table A, which includes the torso, neck, and legs. This value is recorded in Table A. The value obtained from Table A is then added to the weight of the lifted load.
2. Assign a value to Table B, which includes the upper arm, lower arm, and wrist. This value is recorded in Table B. The value obtained from Table B is then added to the Hand Grip value.
3. After obtaining values for Table A and Table B, they are recorded in Table C. The value of C is then added to the Activity Value.
4. Upon adding the C value to the Activity Value, REBA values and corresponding risk categories can be obtained.

   Table V.1 Shows the risk levels and actions needed for each REBA score group.

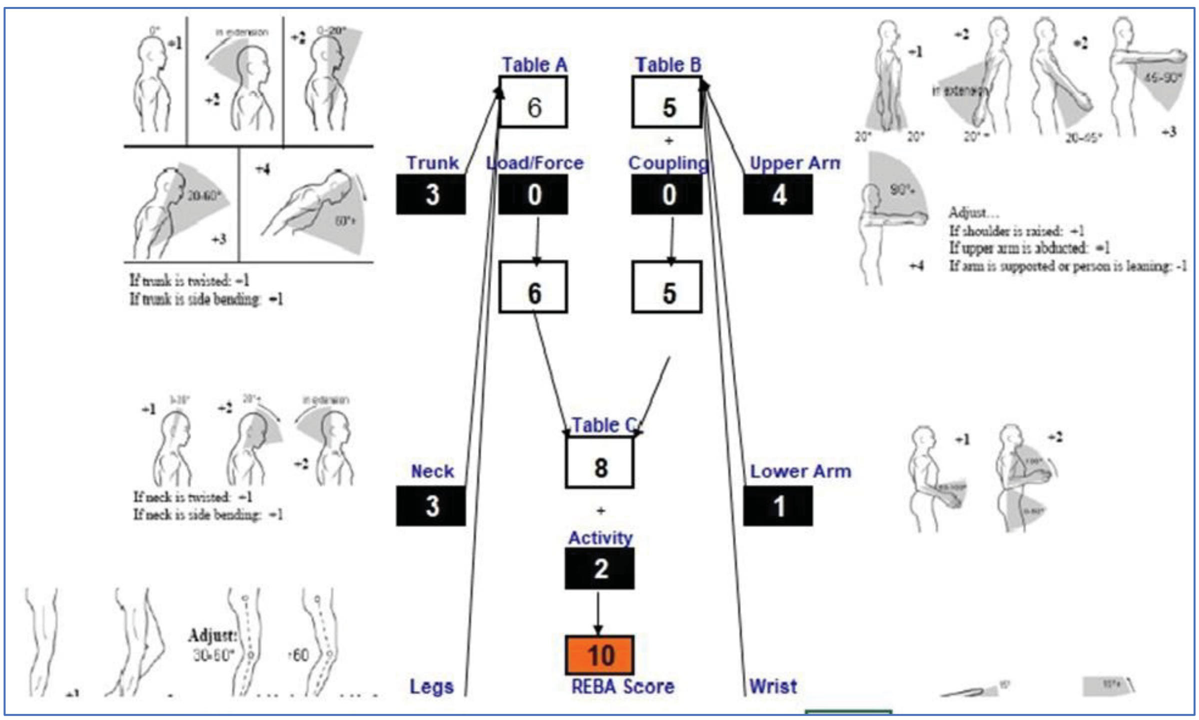
Table V.1 Risk level and actions

REBA Score	Risk Level	Action
1	**Negligible**	**None necessary**
2 – 3	**Low**	**May be necessary**
4 – 7	**Medium**	**Necessary**
8 – 10	**High**	**Necessary soon**
11 – 15	**Very High**	**Necessary now**

3.6 Reba analysis

As a result of REBA analysis for the individual with unusual posture, the action of putting the bracket in place and tightening bolts while checking alignments has a score of 10 for this specific participant. This score has a high risk level and requires necessary actions soon. The activity caused the body to have an unusual posture with the neck bent. REBA scores and details of measurements shown in Figure A.V.1.

Figure A.V.1 REBA scores



ANNEX VI

TWO-HANDED PROCESS CHART

To gain a deeper understanding of the impact of smart glasses on reading instructions and individual workload differences, we analyzed eye tracking and upper limb movements.

Figure A.VI.1 Two hand process charts without glasses

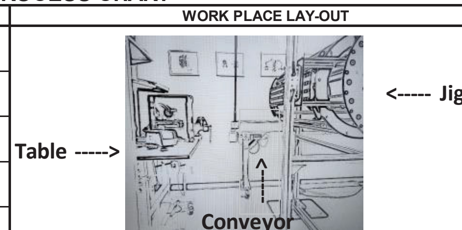
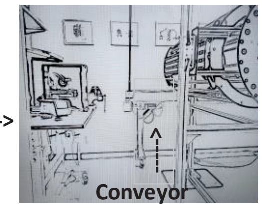
TWO HANDED PROCESS CHART									
					WORK PLACE LAY-OUT				
OPERATION-	Assembly								
LOCATION-	ETS								
OPERATOR-									
CHARTED BY-									
DATE-									
L/H DESCRIPTION	○	⇨	D	▽	○	⇨	D	▽	R/H DESCRIPTION
								•	picks up bolts bin
						•			To the table
picks up bracket				•				•	picks up the ratchet and bolts
positions bracket	•				•				put bolts in
holds the bracket	•				•				uses ratchet to tighten bolts/ uses both ha
checks bolts for any looseness	•					•			puts ratchet in pocket
puts ratchet back on table		•				•			puts ratchet back on table

Figure A.VI.2 Two hand process charts with glasses

TWO HANDED PROCESS CHART

		WORK PLACE LAY-OUT
OPERATION-	Assembly with smart glasses	
LOCATION-	ETS	
OPERATOR-		
CHARTED BY-		
DATE-		

L/H DESCRIPTION	○	⇨	□	▽	○	⇨	□	▽	R/H DESCRIPTION
							•		checking for instruction in smart glasses
								•	Picks up bolts bin from conveyor
						•			To the table
picks up bracket				•				•	picks up the ratchet and bolts
positions bracket	•				•				put bolts in
holds the bracket	•				•				uses ratchet to tighten bolts/ uses both ha
checks bolts for any looseness	•						•		puts ratchet in pocket
puts ratchet back on table		•					•		puts ratchet back on table

ANNEX VII

NASA-TLX

Our study utilized the NASA Scenario Load Index (NASA-TLX) to measure subjective feelings and workload, recognizing the significance of mental workload in influencing performance. Previous research, as cited (Lagomarsino et al., 2021; Sweller et al., 2019; Wittenberg, 2015; Stahn et al., 2021), supports the idea that an increase in mental demand can impact worker efficiency and can induce stress.

At the conclusion of the experiment, each participant was given a NASA Scenario Load Index (NASA-TLX) survey to evaluate the subjective workload they experienced while performing the whole experiment.

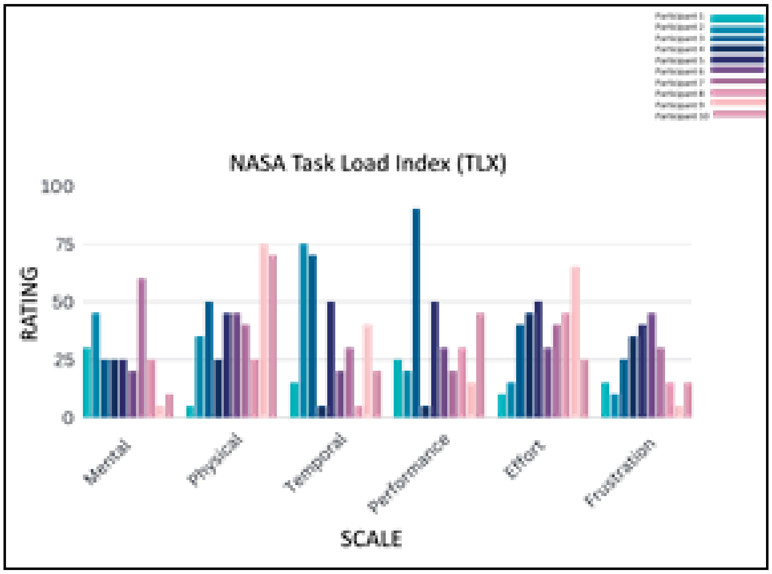
Results

The findings presented in Table A.VII.1 Unweighted NASA-TLX results provide raw ratings for each workload dimension, while weighted results incorporate participants' judgments about the relative importance of these dimensions in an overall workload assessment, offering a more nuanced perspective on workload perception. The choice between them depends on the research or practical context and the specific insights needed. For both the weighted and unweighted NASA-TLX, indicate that overall, the participants experienced more physical demand and effort compared to mental demand and frustration while performing the scenarios. However, the individual responses (Table A.VII.2), varied among the participants.

Table A.VII.1 Weighted and raw global NASA-TLX

Group Score Results			
Weighted		**Raw/Unweighted**	
Overall	35.67	**Overall**	25.00
Diagnostic Subscores		Diagnostic Subscores	
Mental	75.00	Mental	27.00
Physical	137.22	Physical	41.50
Temporal	73.13	Temporal	33.00
Performance	99.50	Performance	33.00
Effort	108.50	Effort	36.50
Frustration	85.63	Frustration	23.50

Table A.VII.2 Scenario Load Index



Results of interpreting both weighted and unweighted scores are as below:

Unweighted Results:

1. Mental Demand: 27 - This score indicates a relatively low mental workload, suggesting that the entire experiment did not require a significant amount of cognitive effort or mental concentration.
2. Physical Demand: 41 - This score indicates a moderate physical workload, implying that the entire experiment involved a fair amount of physical exertion or activities.
3. Temporal Demand: 33 - This score suggests a moderate level of time pressure or urgency during the entire experiment, indicating that participants felt they needed to work at a reasonable pace.
4. Performance: 33 - This score suggests that participants perceived their scenario performance to be satisfactory and successful after the entire experiment.

5. Effort: 36 - This score indicates a moderate level of effort exerted by the participants to complete the entire experiment.
6. Frustration: 23 - This score suggests a relatively low level of frustration or dissatisfaction experienced by participants during the entire experiment.

Weighted Results:

1. Mental Demand: 75 - This weighted score emphasizes that the mental workload was perceived as relatively high when considering the entire experiment's characteristics and requirements.
2. Physical Demand: 137.22 - The weighted score indicates a substantial physical workload, showing that the entire experiment involved significant physical effort or demands.
3. Temporal Demand: 73.13 - This weighted score highlights that the temporal demands, such as time pressure, were relatively high during the entire experiment.
4. Performance: 99.50 - The weighted score reflects that participants felt reasonably satisfied with their performance during the entire experiment.
5. Effort: 108.50 - This weighted score underscores that participants perceived a significant level of effort was required to complete the entire experiment.
6. Frustration: 85.63 - The weighted score suggests that participants experienced some level of frustration or dissatisfaction during the experiment, but it was not excessively high.

The unweighted scores indicate relatively low mental demand, moderate physical demand, and moderate temporal demand. Participants reported a moderate level of effort and relatively low frustration throughout the experiment. However, when considering the weighted scores, it becomes evident that the mental demand, physical demand, temporal demand, effort, and frustration were perceived as relatively higher. This suggests that the overall workload and demands of the experiment were more significant when accounting for their relative importance and impact on participants' experiences.

Globally, the weighted and unweighted NASA-TLX were high for the physical and effort indicators. Participants' individual scores however show important differences.

However, it is important to note that adverse effects on performance by increasing the cognitive load, leading to fatigue and decreased attention can be results of visual complexity (Eswaran et al., 2023). In our study, the impacts of the whole experiment are more pronounced at the level of perceived physical aspects, mental demand was also relatively high. Our study utilized the NASA Scenario Load Index (NASA-TLX) to measure subjective feelings and workload, recognizing the significance of mental workload in influencing performance.

NASA-TLX Questionaire

Rating Scale Definitions

Title	Descriptions
MENTAL DEMAND	How much mental and perceptual activity was required (e.g., thinking, deciding, calculating, remembering, looking, searching, etc.)? Was the task easy or demanding, simple or complex, exacting or forgiving?
PHYSICAL DEMAND	How much physical activity was required (e.g., pushing, pulling, turning, controlling, activating, etc.)? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?
TEMPORAL DEMAND	How much time pressure did you feel due to the rate or pace at which the tasks or task elements occurred? Was the pace slow and leisurely or rapid and frantic?
PERFORMANCE	How successful do you think you were in accomplishing the goals of the task set by the experimenter (or yourself)? How satisfied were you with your performance in accomplishing these goals?
EFFORT	How hard did you have to work (mentally and physically) to accomplish your level of performance?
FRUSTRATION LEVEL	How insecure, discouraged, irritated, stressed and annoyed versus secure, gratified, content, relaxed and complacent did you feel during the task?

Place a mark at the desired point on each scale:

MENTAL DEMAND

Low High

PHYSICAL DEMAND

Low High

TEMPORAL DEMAND

Low High

PERFORMANCE

Good Poor

EFFORT

Low High

FRUSTRATION

Low High

ANNEX VIII

ETHICS CERTIFICATE

Comité d'éthique de la recherche
École de technologie supérieure

Le 27 juillet 2022

Projet :	**Modeling and qualification of future digitalized assembly work**
Chercheur responsable :	**Sylvie Nadeau, professeure au département de génie mécanique – École de technologie supérieure (ÉTS)**
Étudiante :	**Nasim Khoddammohammadi, étudiante à la maîtrise – ÉTS**
Référence :	**H20220607** *Demande :* ***Nouvelle***

APPROBATION FINALE

Madame Nadeau,

Nous accusons réception du dossier modifié et des documents demandés selon les recommandations émises le 13 juillet 2022 par le Comité d'éthique de la recherche de l'École de technologie supérieure (CÉR de l'ÉTS). Après révision, le dossier est jugé conforme aux exigences éthiques. J'ai donc le plaisir de vous informer que **votre projet est approuvé et que vous pouvez procéder au recrutement de vos participants**.

Vous trouverez, jointe à la présente, une copie du formulaire d'information et de consentement **approuvé par le CÉR de l'ÉTS** (*version PDF datée du 27 juillet 2022*). Veuillez utiliser cette version du document pour le recrutement.

L'approbation éthique de votre projet est valable pour une année à compter de la date d'approbation finale. Selon l'état d'avancement de votre projet à la date mentionnée ci-dessous, vous devrez fournir au CÉR de l'ÉTS un rapport de suivi annuel pour demander le renouvellement de l'approbation éthique ou la fermeture du dossier.

En acceptant la présente approbation éthique, vous vous engagez à :

- Observer une **conduite responsable** tout au long de vos travaux de recherche;
- Informer dès que possible le CÉR de **tout changement** apporté au projet ou **tout évènement imprévu** qui surviendrait au cours d'une séance de collecte de données;
- Respecter les **conditions de confidentialité et de protection des renseignements et des données**, telles qu'énoncées dans le dossier et approuvées par le CÉR;
- Conserver cette approbation éthique **valide au moins jusqu'à la publication des premiers résultats** de la recherche.

Si vous avez des questions ou des préoccupations éthiques au cours de votre projet, veuillez contacter le bureau coordonnateur du CÉR par courriel à l'adresse cer@etsmtl.ca ou par téléphone (514) 396-8800 poste 7129.

Veuillez agréer, Madame Nadeau, l'expression de mes sentiments les meilleurs.

Erika Olivaux, M.A.
Coordonnatrice, Comité d'éthique de la recherche,
École de technologie supérieure

ÉCHÉANCE DE L'APPROBATION ÉTHIQUE
(Date limite pour la remise du rapport annuel)
27 juillet 2023

cc : Ghyslain Gagnon, Doyen de la recherche
Mathias Glaus, Président du CÉR

pj : Formulaire d'information et de consentement approuvé

Comité d'éthique de la recherche
École de technologie supérieure

19 juillet 2023

Projet :	**Modélisation et qualification des futures tâches d'assemblage numérisées**
Chercheur responsable :	**Sylvie Nadeau, professeure au département de génie mécanique – École de technologie supérieure (ÉTS)**
Étudiante :	**Nasim Khoddammohammadi, étudiante à la maîtrise – ÉTS**
Référence :	**H20220607** *Demande :* ***Renouvellement 2023-2024***

APPROBATION FINALE

Professeure Nadeau,

Nous accusons réception de la demande de renouvellement de l'approbation éthique pour le projet de recherche mentionné en rubrique. Le document soumis est conforme aux attentes du Comité d'éthique de la recherche de l'École de technologie supérieure (CÉR de l'ÉTS). J'ai donc le plaisir de vous informer que le renouvellement de l'approbation éthique de votre projet est **accordé sans condition jusqu'au 19 juillet 2024**.

Selon l'état d'avancement de votre projet à la date d'échéance de l'approbation, vous devrez fournir au CÉR de l'ÉTS un rapport de suivi annuel pour demander le renouvellement de l'approbation éthique ou la fermeture du dossier.

Pour rappel, en acceptant la présente approbation éthique, vous vous engagez à :

- Observer une **conduite responsable** tout au long de vos travaux de recherche;
- Informer dès que possible le CÉR de **tout changement** apporté au projet ou **tout évènement imprévu** qui surviendrait au cours d'une séance de collecte de données;
- Respecter les **conditions de confidentialité et de protection des renseignements et des données**, telles qu'énoncées dans le dossier et approuvées par le CÉR;
- Conserver cette approbation éthique **valide au moins jusqu'à la publication des premiers résultats** de la recherche.

Si vous avez des questions ou des préoccupations éthiques au cours de votre projet, veuillez contacter le bureau coordonnateur du CÉR de l'ÉTS par courriel à l'adresse cer@etsmtl.ca ou par téléphone au **(514) 396-8800 poste 7129**.

cc : Ghyslain Gagnon, Doyen de la recherche
Mathias Glaus, Président du CÉR

Veuillez agréer, Professeure Nadeau, l'expression de mes sentiments les meilleurs.

Chantal Lefebvre, M. Sc.

Coordonnatrice, Comité d'éthique de la recherche
École de technologie supérieure

ÉCHÉANCE DE L'APPROBATION ÉTHIQUE
(Date limite pour la remise du rapport annuel)
19 juillet 2024

cc : Ghyslain Gagnon, Doyen de la recherche
Sylvie Ratté, Présidente du CÉR par intérim

2022 Par-Q+/2022Q-AAP+

2022 PAR-Q+

The Physical Activity Readiness Questionnaire for Everyone

The health benefits of regular physical activity are clear; more people should engage in physical activity every day of the week. Participating in physical activity is very safe for MOST people. This questionnaire will tell you whether it is necessary for you to seek further advice from your doctor OR a qualified exercise professional before becoming more physically active.

GENERAL HEALTH QUESTIONS

Please read the 7 questions below carefully and answer each one honestly: check YES or NO.	YES	NO
1) Has your doctor ever said that you have a heart condition ☐ **OR** high blood pressure ☐?	☐	☐
2) Do you feel pain in your chest at rest, during your daily activities of living, **OR** when you do physical activity?	☐	☐
3) Do you lose balance because of dizziness **OR** have you lost consciousness in the last 12 months? Please answer **NO** if your dizziness was associated with over-breathing (including during vigorous exercise).	☐	☐
4) Have you ever been diagnosed with another chronic medical condition (other than heart disease or high blood pressure)? **PLEASE LIST CONDITION(S) HERE:** ______	☐	☐
5) Are you currently taking prescribed medications for a chronic medical condition? **PLEASE LIST CONDITION(S) AND MEDICATIONS HERE:** ______	☐	☐
6) Do you currently have (or have had within the past 12 months) a bone, joint, or soft tissue (muscle, ligament, or tendon) problem that could be made worse by becoming more physically active? Please answer **NO** if you had a problem in the past, but it **does not limit your current ability** to be physically active. **PLEASE LIST CONDITION(S) HERE:** ______	☐	☐
7) Has your doctor ever said that you should only do medically supervised physical activity?	☐	☐

If you answered NO to all of the questions above, you are cleared for physical activity.
Please sign the PARTICIPANT DECLARATION. You do not need to complete Pages 2 and 3.

- Start becoming much more physically active – start slowly and build up gradually.
- Follow Global Physical Activity Guidelines for your age (https://www.who.int/publications/i/item/9789240015128).
- You may take part in a health and fitness appraisal.
- If you are over the age of 45 yr and NOT accustomed to regular vigorous to maximal effort exercise, consult a qualified exercise professional before engaging in this intensity of exercise.
- If you have any further questions, contact a qualified exercise professional.

PARTICIPANT DECLARATION
If you are less than the legal age required for consent or require the assent of a care provider, your parent, guardian or care provider must also sign this form.

I, the undersigned, have read, understood to my full satisfaction and completed this questionnaire. I acknowledge that this physical activity clearance is valid for a maximum of 12 months from the date it is completed and becomes invalid if my condition changes. I also acknowledge that the community/fitness center may retain a copy of this form for its records. In these instances, it will maintain the confidentiality of the same, complying with applicable law.

NAME ______________________ DATE ______________

SIGNATURE ______________________ WITNESS ______________

SIGNATURE OF PARENT/GUARDIAN/CARE PROVIDER ______________________

If you answered YES to one or more of the questions above, COMPLETE PAGES 2 AND 3.

Delay becoming more active if:

- You have a temporary illness such as a cold or fever; it is best to wait until you feel better.
- You are pregnant - talk to your health care practitioner, your physician, a qualified exercise professional, and/or complete the ePARmed-X+ at www.eparmedx.com before becoming more physically active.
- Your health changes - answer the questions on Pages 2 and 3 of this document and/or talk to your doctor or a qualified exercise professional before continuing with any physical activity program.

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01-11-2021

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FOLLOW-UP QUESTIONS ABOUT YOUR MEDICAL CONDITION(S)

1.	**Do you have Arthritis, Osteoporosis, or Back Problems?** If the above condition(s) is/are present, answer questions 1a-1c If **NO** ☐ go to question 2	
1a.	Do you have difficulty controlling your condition with medications or other physician-prescribed therapies? (Answer **NO** if you are not currently taking medications or other treatments)	YES ☐ NO ☐
1b.	Do you have joint problems causing pain, a recent fracture or fracture caused by osteoporosis or cancer, displaced vertebra (e.g., spondylolisthesis), and/or spondylolysis/pars defect (a crack in the bony ring on the back of the spinal column)?	YES ☐ NO ☐
1c.	Have you had steroid injections or taken steroid tablets regularly for more than 3 months?	YES ☐ NO ☐
2.	**Do you currently have Cancer of any kind?** If the above condition(s) is/are present, answer questions 2a-2b If **NO** ☐ go to question 3	
2a.	Does your cancer diagnosis include any of the following types: lung/bronchogenic, multiple myeloma (cancer of plasma cells), head, and/or neck?	YES ☐ NO ☐
2b.	Are you currently receiving cancer therapy (such as chemotheraphy or radiotherapy)?	YES ☐ NO ☐
3.	**Do you have a Heart or Cardiovascular Condition? This includes Coronary Artery Disease, Heart Failure, Diagnosed Abnormality of Heart Rhythm** If the above condition(s) is/are present, answer questions 3a-3d If **NO** ☐ go to question 4	
3a.	Do you have difficulty controlling your condition with medications or other physician-prescribed therapies? (Answer **NO** if you are not currently taking medications or other treatments)	YES ☐ NO ☐
3b.	Do you have an irregular heart beat that requires medical management? (e.g., atrial fibrillation, premature ventricular contraction)	YES ☐ NO ☐
3c.	Do you have chronic heart failure?	YES ☐ NO ☐
3d.	Do you have diagnosed coronary artery (cardiovascular) disease and have not participated in regular physical activity in the last 2 months?	YES ☐ NO ☐
4.	**Do you currently have High Blood Pressure?** If the above condition(s) is/are present, answer questions 4a-4b If **NO** ☐ go to question 5	
4a.	Do you have difficulty controlling your condition with medications or other physician-prescribed therapies? (Answer **NO** if you are not currently taking medications or other treatments)	YES ☐ NO ☐
4b.	Do you have a resting blood pressure equal to or greater than 160/90 mmHg with or without medication? (Answer **YES** if you do not know your resting blood pressure)	YES ☐ NO ☐
5.	**Do you have any Metabolic Conditions? This includes Type 1 Diabetes, Type 2 Diabetes, Pre-Diabetes** If the above condition(s) is/are present, answer questions 5a-5e If **NO** ☐ go to question 6	
5a.	Do you often have difficulty controlling your blood sugar levels with foods, medications, or other physician-prescribed therapies?	YES ☐ NO ☐
5b.	Do you often suffer from signs and symptoms of low blood sugar (hypoglycemia) following exercise and/or during activities of daily living? Signs of hypoglycemia may include shakiness, nervousness, unusual irritability, abnormal sweating, dizziness or light-headedness, mental confusion, difficulty speaking, weakness, or sleepiness.	YES ☐ NO ☐
5c.	Do you have any signs or symptoms of diabetes complications such as heart or vascular disease and/or complications affecting your eyes, kidneys, **OR** the sensation in your toes and feet?	YES ☐ NO ☐
5d.	Do you have other metabolic conditions (such as current pregnancy-related diabetes, chronic kidney disease, or liver problems)?	YES ☐ NO ☐
5e.	Are you planning to engage in what for you is unusually high (or vigorous) intensity exercise in the near future?	YES ☐ NO ☐

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2022 PAR-Q+

6.	**Do you have any Mental Health Problems or Learning Difficulties?** This includes Alzheimer's, Dementia, Depression, Anxiety Disorder, Eating Disorder, Psychotic Disorder, Intellectual Disability, Down Syndrome If the above condition(s) is/are present, answer questions 6a-6b — If **NO** ☐ go to question 7	
6a.	Do you have difficulty controlling your condition with medications or other physician-prescribed therapies? (Answer **NO** if you are not currently taking medications or other treatments)	YES ☐ NO ☐
6b.	Do you have Down Syndrome **AND** back problems affecting nerves or muscles?	YES ☐ NO ☐
7.	**Do you have a Respiratory Disease?** *This includes Chronic Obstructive Pulmonary Disease, Asthma, Pulmonary High Blood Pressure* If the above condition(s) is/are present, answer questions 7a-7d — If **NO** ☐ go to question 8	
7a.	Do you have difficulty controlling your condition with medications or other physician-prescribed therapies? (Answer **NO** if you are not currently taking medications or other treatments)	YES ☐ NO ☐
7b.	Has your doctor ever said your blood oxygen level is low at rest or during exercise and/or that you require supplemental oxygen therapy?	YES ☐ NO ☐
7c.	If asthmatic, do you currently have symptoms of chest tightness, wheezing, laboured breathing, consistent cough (more than 2 days/week), or have you used your rescue medication more than twice in the last week?	YES ☐ NO ☐
7d.	Has your doctor ever said you have high blood pressure in the blood vessels of your lungs?	YES ☐ NO ☐
8.	**Do you have a Spinal Cord Injury?** *This includes Tetraplegia and Paraplegia* If the above condition(s) is/are present, answer questions 8a-8c — If **NO** ☐ go to question 9	
8a.	Do you have difficulty controlling your condition with medications or other physician-prescribed therapies? (Answer **NO** if you are not currently taking medications or other treatments)	YES ☐ NO ☐
8b.	Do you commonly exhibit low resting blood pressure significant enough to cause dizziness, light-headedness, and/or fainting?	YES ☐ NO ☐
8c.	Has your physician indicated that you exhibit sudden bouts of high blood pressure (known as Autonomic Dysreflexia)?	YES ☐ NO ☐
9.	**Have you had a Stroke?** *This includes Transient Ischemic Attack (TIA) or Cerebrovascular Event* If the above condition(s) is/are present, answer questions 9a-9c — If **NO** ☐ go to question 10	
9a.	Do you have difficulty controlling your condition with medications or other physician-prescribed therapies? (Answer **NO** if you are not currently taking medications or other treatments)	YES ☐ NO ☐
9b.	Do you have any impairment in walking or mobility?	YES ☐ NO ☐
9c.	Have you experienced a stroke or impairment in nerves or muscles in the past 6 months?	YES ☐ NO ☐
10.	**Do you have any other medical condition not listed above or do you have two or more medical conditions?** If you have other medical conditions, answer questions 10a-10c — If **NO** ☐ read the Page 4 recommendations	
10a.	Have you experienced a blackout, fainted, or lost consciousness as a result of a head injury within the last 12 months **OR** have you had a diagnosed concussion within the last 12 months?	YES ☐ NO ☐
10b.	Do you have a medical condition that is not listed (such as epilepsy, neurological conditions, kidney problems)?	YES ☐ NO ☐
10c.	Do you currently live with two or more medical conditions?	YES ☐ NO ☐

PLEASE LIST YOUR MEDICAL CONDITION(S) AND ANY RELATED MEDICATIONS HERE: ______________________

____

GO to Page 4 for recommendations about your current medical condition(s) and sign the PARTICIPANT DECLARATION.

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If you answered NO to all of the FOLLOW-UP questions (pgs. 2-3) about your medical condition, you are ready to become more physically active - sign the PARTICIPANT DECLARATION below:

- It is advised that you consult a qualified exercise professional to help you develop a safe and effective physical activity plan to meet your health needs.
- You are encouraged to start slowly and build up gradually - 20 to 60 minutes of low to moderate intensity exercise, 3-5 days per week including aerobic and muscle strengthening exercises.
- As you progress, you should aim to accumulate 150 minutes or more of moderate intensity physical activity per week.
- If you are over the age of 45 yr and **NOT** accustomed to regular vigorous to maximal effort exercise, consult a qualified exercise professional before engaging in this intensity of exercise.

If you answered **YES** to **one or more of the follow-up questions** about your medical condition:
You should seek further information before becoming more physically active or engaging in a fitness appraisal. You should complete the specially designed online screening and exercise recommendations program - the **ePARmed-X+ at www.eparmedx.com** and/or visit a qualified exercise professional to work through the ePARmed-X+ and for further information.

Delay becoming more active if:

- You have a temporary illness such as a cold or fever; it is best to wait until you feel better.
- You are pregnant - talk to your health care practitioner, your physician, a qualified exercise professional, and/or complete the ePARmed-X+ **at www.eparmedx.com** before becoming more physically active.
- Your health changes - talk to your doctor or qualified exercise professional before continuing with any physical activity program.

- You are encouraged to photocopy the PAR-Q+. You must use the entire questionnaire and NO changes are permitted.
- The authors, the PAR-Q+ Collaboration, partner organizations, and their agents assume no liability for persons who undertake physical activity and/or make use of the PAR-Q+ or ePARmed-X+. If in doubt after completing the questionnaire, consult your doctor prior to physical activity.

PARTICIPANT DECLARATION

- All persons who have completed the PAR-Q+ please read and sign the declaration below.
- If you are less than the legal age required for consent or require the assent of a care provider, your parent, guardian or care provider must also sign this form.

I, the undersigned, have read, understood to my full satisfaction and completed this questionnaire. I acknowledge that this physical activity clearance is valid for a maximum of 12 months from the date it is completed and becomes invalid if my condition changes. I also acknowledge that the community/fitness center may retain a copy of this form for records. In these instances, it will maintain the confidentiality of the same, complying with applicable law.

NAME ______________________________ DATE ______________________________

SIGNATURE ______________________________ WITNESS ______________________________

SIGNATURE OF PARENT/GUARDIAN/CARE PROVIDER ______________________________

For more information, please contact
www.eparmedx.com
Email: eparmedx@gmail.com

Citation for PAR-Q+
Warburton DER, Jamnik VK, Bredin SSD, and Gledhill N on behalf of the PAR-Q+ Collaboration. The Physical Activity Readiness Questionnaire for Everyone (PAR-Q+) and Electronic Physical Activity Readiness Medical Examination (ePARmed-X+). Health & Fitness Journal of Canada 4(2):3-23, 2011.

The PAR-Q+ was created using the evidence-based AGREE process (1) by the PAR-Q+ Collaboration chaired by Dr. Darren E. R. Warburton with Dr. Norman Gledhill, Dr. Veronica Jamnik, and Dr. Donald C. McKenzie (2). Production of this document has been made possible through financial contributions from the Public Health Agency of Canada and the BC Ministry of Health Services. The views expressed herein do not necessarily represent the views of the Public Health Agency of Canada or the BC Ministry of Health Services.

Key References

1. Jamnik VK, Warburton DER, Makarski J, McKenzie DC, Shephard RJ, Stone J, and Gledhill N. Enhancing the effectiveness of clearance for physical activity participation; background and overall process. APNM 36(S1):S3-S13, 2011.
2. Warburton DER, Gledhill N, Jamnik VK, Bredin SSD, McKenzie DC, Stone J, Charlesworth S, and Shephard RJ. Evidence-based risk assessment and recommendations for physical activity clearance; Consensus Document. APNM 36(S1):S266-s298, 2011.
3. Chisholm DM, Collis ML, Kulak LL, Davenport W, and Gruber N. Physical activity readiness. British Columbia Medical Journal. 1975;17:375-378.
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CONSENT FORM

Le génie pour l'industrie

Projet H20220607
APPROUVÉ le 27 juillet 2022
Comité d'éthique de la recherche – ÉTS

FORMULAIRE D'INFORMATION ET DE CONSENTEMENT

TITRE DU PROJET DE RECHERCHE

Modélisation et qualification des futures tâches d'assemblage numérisées

CHERCHEUSE RESPONSABLE

Sylvie Nadeau, professeure au département de Génie mécanique – École de technologie supérieure (ÉTS), responsable du Laboratoire de génie des facteurs humains appliqués

ÉTUDIANTE

Nasim Khoddammohammadi, étudiante à la maîtrise au département de Génie mécanique – ÉTS

FINANCEMENT

La chercheuse responsable, Pr. Nadeau, a reçu du financement du Conseil de recherche en sciences naturelles et en génie du Canada (CRSNG) pour mener à bien ce projet de recherche.

INTRODUCTION

Nous vous invitons à participer à un projet de recherche. Cependant, avant d'accepter de participer à ce projet et de signer ce formulaire d'information et de consentement, veuillez prendre le temps de lire, de comprendre et de considérer attentivement les renseignements qui suivent.

Ce formulaire peut contenir des mots que vous ne comprenez pas. Nous vous invitons à poser toutes les questions que vous jugerez utiles à la chercheuse responsable de ce projet ou à un membre de l'équipe de recherche, et à leur demander de vous expliquer tout mot ou renseignement qui n'est pas clair.

NATURE ET OBJECTIFS DU PROJET DE RECHERCHE

Le projet vise à recueillir des connaissances et des données scientifiques sur l'aspect pratique des dispositifs portables intelligents (*wearables)* dans l'industrie. L'objectif est d'identifier les limites de l'utilisation de ces dispositifs et de les intégrer dans un environnement de travail hybride (équipements mécaniques, pneumatiques et automatisés) dans une perspective de santé et de sécurité au travail et tenant compte des aspects opérationnels.

Pour réaliser le projet, nous avons l'intention de recruter 45 participants, hommes et femmes, âgés de 20 à 65 ans.

DÉROULEMENT DU PROJET DE RECHERCHE

1. Lieu de réalisation du projet de recherche et durée de la participation

Ce projet de recherche se déroulera au Laboratoire de génie des facteurs humains appliqués (A-2232). Votre participation au projet durera entre 1h30 et 2h et nécessitera deux rencontres.

2. Nature de votre participation

1. Première rencontre (30 minutes)

Nous vous demanderons de remplir un questionnaire d'admissibilité sur vos antécédents de santé et vos aptitudes physiques. Nous mesurerons également la distance entre votre coude et le sol afin d'ajuster, avant la visite au laboratoire, le gabarit d'assemblage privilégiant ainsi une posture ergonomique.

À ce stade, il se peut que vous ne soyez pas admissible à participer au projet de recherche. Le cas échéant, nous vous en expliquerons les raisons.

2. Deuxième rencontre : Visite au laboratoire (60 à 90 minutes)

Tout d'abord, nous vous demanderons de porter un système d'oculométrie. Nous pourrions également vous demander de porter des lunettes intelligentes (Fig. 1).

Fig. 1. Système d'oculométrie (à gauche) et lunettes intelligentes (à droite).

Ensuite, nous vous demanderons d'assembler des supports en L avec des boulons sur un gabarit d'assemblage (Fig. 2 et 3). Vous utiliserez la clé dynamométrique manuelle (Fig. 4) et la clé dynamométrique pneumatique (Fig. 5) avec et sans limiteur de couple.

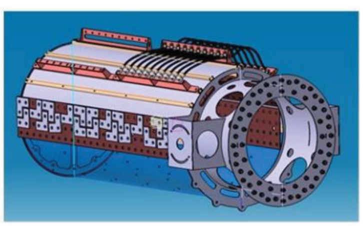

Figure 2. Gabarit d'assemblage et composantes en L à assembler

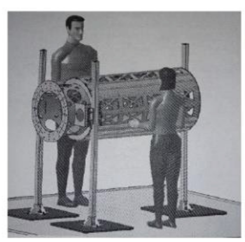

Figure 3. Gabarit d'assemblage

Figure 4. Clé dynamométrique manuelle

Figure 5. Clés dynamométrique pneumatique

Il y aura 2 ou trois tâches à accomplir et chacune devra être répétée 20 fois. Au cours de cette étape, nous enregistrerons vos mouvements oculaires, nous filmerons les mouvements de vos membres supérieurs et nous mesurerons le temps avec un chronomètre.

Enfin, nous vous demanderons de remplir un questionnaire sur votre perception de la tâche accomplie.

UTILISATION DES ENREGISTREMENTS

Le but premier des enregistrements vidéo collectés dans le cadre du projet est de nous permettre de valider les différentes données.

Par ailleurs, ces enregistrements ne seront pas utilisés à des fins d'enseignement, de recherche ou lors de conférences scientifiques.

AVANTAGES ET BÉNÉFICES ASSOCIÉS AU PROJET DE RECHERCHE

Il se peut que vous retiriez un bénéfice personnel de votre participation à ce projet de recherche, mais nous ne pouvons vous l'assurer. Par ailleurs, les résultats obtenus contribueront à l'avancement des connaissances scientifiques dans ce domaine de recherche.

INCONVÉNIENTS ASSOCIÉS AU PROJET DE RECHERCHE

Votre participation à cette étude pourrait occasionner certains inconvénients en termes de temps.

RISQUES ASSOCIÉS AU PROJET DE RECHERCHE

Il y a un risque de fatigue dans les bras en utilisant les clés dynamométriques. De plus, le bruit et les légères vibrations causées par le couple de serrage de l'outil pneumatique pourraient être inconfortables. Pour atténuer ce risque, votre temps de participation a été limité au plus court possible.

De plus, il y a un risque de ressentir de la fatigue oculaire en utilisant les lunettes intelligentes. Si vous le souhaitez, nous pouvons planifier une réunion pour vérifier votre confort avec les lunettes intelligentes avant la réunion de test. Si vous n'êtes pas à l'aise, vous pouvez faire une pause et retirer les lunettes à tout moment.

Participation volontaire et droit de retrait

Votre participation à ce projet de recherche est volontaire. Vous êtes donc libre de refuser d'y participer. Vous pouvez également vous retirer de ce projet à n'importe quel moment, sans avoir à donner de raisons, en informant l'équipe de recherche.

La chercheuse responsable de ce projet de recherche, le Comité d'éthique de la recherche de l'École de technologie supérieure ou organisme de financement peuvent mettre fin à votre participation, sans votre consentement. Cela peut se produire si de nouvelles découvertes ou informations indiquent que votre participation au projet n'est plus dans votre intérêt, si vous ne respectez pas les consignes du projet de recherche ou encore s'il existe des raisons administratives d'abandonner le projet.

Si vous vous retirez du projet ou êtes retiré(e) du projet, l'information et le matériel déjà recueillis dans le cadre de ce projet seront néanmoins conservés, analysés ou utilisés pour assurer l'intégrité du projet.

Toute nouvelle connaissance acquise durant le déroulement du projet qui pourrait avoir un impact sur votre décision de continuer à participer à ce projet vous sera communiquée rapidement.

Confidentialité

Durant votre participation à ce projet de recherche, la chercheuse responsable ainsi que les membres de l'équipe de recherche recueilleront, dans un dossier de recherche, les renseignements vous concernant et nécessaires pour répondre aux objectifs scientifiques de ce projet de recherche.

Ces renseignements peuvent comprendre votre nom, âge, genre, courriel ainsi que les données de toutes les activités de recherche réalisées dans le cadre du projet.

Tous les renseignements recueillis demeureront confidentiels, dans les limites prévues par la loi. Afin de préserver votre identité et la confidentialité de vos renseignements, un numéro de code vous sera attribué. La clé du code reliant votre nom à votre dossier de recherche sera conservée par la chercheuse responsable de ce projet de recherche jusqu'à la fin de l'étude, ensuite elle sera détruite.

Ces données de recherche seront conservées pendant au moins 10 ans par la chercheuse responsable de ce projet de recherche.

Les données de recherche pourront être publiées ou faire l'objet de discussions scientifiques, mais il ne sera pas possible de vous identifier.

À des fins de surveillance, de contrôle, de protection, de sécurité, votre dossier de recherche pourra être consulté par une personne mandatée par des organismes réglementaires ainsi que par des représentants de l'organisme subventionnaire, de l'École de technologie supérieure ou du Comité d'éthique de la recherche. Ces personnes et ces organismes adhèrent à une politique de confidentialité.

Vous avez le droit de consulter votre dossier de recherche pour vérifier les renseignements recueillis et les faire rectifier au besoin.

Compensation

Vous ne recevrez pas de compensation financière pour votre participation à ce projet de recherche.

En cas de préjudice

Si vous deviez subir quelque préjudice que ce soit dû à votre participation au projet de recherche, vous recevrez tous les soins et services requis par votre état de santé.

En acceptant de participer à ce projet de recherche, vous ne renoncez à aucun de vos droits légaux et ne libérez pas le chercheur en charge du projet, l'École de technologie supérieure et l'organisme de financement de leurs responsabilités civiles et professionnelles.

Procédures en cas d'urgence médicale

L'École de technologie supérieure n'offre pas de services d'urgence. Par conséquent, advenant une condition médicale qui nécessiterait des soins immédiats, les premiers soins vous seront dispensés par le personnel en place et des dispositions seront prises afin de vous transférer, si nécessaire, aux urgences d'un hôpital avoisinant.

Suivi éthique

Le Comité d'éthique de la recherche de l'École de technologie supérieure a approuvé ce projet de recherche et en assure le suivi.

Personnes-ressources

Pour toute question en lien avec le projet de recherche, vous pouvez contacter la chercheuse responsable, Pr. Nadeau, au (514) 396-8672 ou sylvie.nadeau@etsmtl.ca. Vous pouvez également contacter Nasim Khoddammohammadi at nasim.khoddammohammadi.1@ens.etsmtl.ca.

Pour toute question en lien avec vos droits en tant que participant à la recherche, vous pouvez contacter le Comité d'éthique de la recherche de l'École de technologie supérieure par courriel à l'adresse cer@etsmtl.ca ou par téléphone au (514) 396-8800 poste 7129.

CONSENTEMENT

Participant(e)

J'ai lu le présent formulaire de consentement et j'ai disposé de suffisamment de renseignements et du temps nécessaire pour prendre ma décision. Après réflexion, je consens volontairement à participer à ce projet de recherche, aux conditions énoncées.

Nom du(de la) participant(e)	*Signature*	*Date*

Personne qui obtient le consentement (si différente de la chercheuse responsable)

J'ai expliqué au(à la) participant(e) tous les aspects pertinents de la recherche et j'ai répondu aux questions qu'il(elle) m'a posées.

Sylvie Nadeau, ing., Ph.D.	*Signature*	*Date*

Signature et engagement de la chercheuse responsable de ce projet de recherche

Je certifie qu'on a expliqué au(à la) participant(e) le présent formulaire d'information et de consentement, que l'on a répondu aux questions qu'il(elle) avait.

Je m'engage, avec l'équipe de recherche, à respecter ce qui a été convenu au formulaire d'information et de consentement et à remettre une copie signée du présent formulaire au(à la) participant(e).

Sylvie Nadeau, ing., Ph.D.	*Signature*	*Date*

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