Investigating the feasibility of performing ergonomic assessment in virtual reality

by

Kathryn Lieffrig

A thesis submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Major: Industrial Engineering

Program of Study Committee:
Stephen B. Gilbert, Major Professor
Richard Stone
Eliot Winer

The student author, whose presentation of the scholarship herein was approved by the program of study committee, is solely responsible for the content of this thesis. The Graduate College will ensure this thesis is globally accessible and will not permit alterations after a degree is conferred.

Iowa State University

Ames, Iowa

2023

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

NOMENCLATURE

DHM	Digital Human Models
EMG	Electromyography
HCD	Human Centered Design
HMD	Head Mounted Display (VR Headset)
MSD	Musculoskeletal Disorder
NIOSH	National Institute for Occupational Safety and Health
OWAS	Ovako's Work Posture Analysis System
PEAT	Portable Ergonomic Assessment Tool
REBA	Rapid Entire Body Assessment
RULA	Rapid Upper Limb Assessment
VAPA-LP	Virtual Assembly Process Assessment for Large Parts
VR	Virtual Reality
VRAC	Virtual Reality Application Center

ACKNOWLEDGMENTS

I would like to begin by thanking my committee chair, Stephen Gilbert, for all of the guidance and support provided throughout this research study. You have taught me the true meaning of academia and helped me discover my passion for research. I would also like to thank my committee members Richard Stone and Eliot Winer. This research would not have been possible without their support and incredible wealth of knowledge. I would also like to thank my Undergraduate Research Assistants, Madison Bemis, Olivia Poppen, and Tatum Englund, for their dedication and hard work on the project. Finally, I would like to acknowledge and thank Glen Galvin for his contribution developing our lab and workspace.

Additionally, I would like to thank the IMSE and VRAC department faculty at Iowa State University. I have received so much encouragement, support, and advice throughout both my bachelor's and master's programs here and couldn't be more grateful for this experience.

Finally, I would like to thank my parents, Sherri and Jim Lieffrig, for their incredible support throughout my continued education. Your unwavering faith in my abilities have encouraged me to never stop achieving my goals. Thank you to my brother Andy, for teaching me strength and determination. Thank you to my partner, Aaron, for being by my side throughout my entire college education. I would not be who I am today without their constant encouragement.

ABSTRACT

The utilization of virtual reality technology has been drastically increasing in a variety of industries and applications. The objective of this research is to investigate if virtual reality is a feasible substitute for physical ergonomic assessment. Additionally, this research looks to compare three different forms of analysis tools to evaluate how they comparatively perform in a physical and virtual space.

Prior research has been conducted in relation to virtual reality and ergonomics, however little has been done to replicate and assess real world applications. A custom product was fabricated for this research to serve as the assembly component. Once a physical workspace and workbench were established, the space was replicated and rendered in a virtual environment. Participants assembled the product in both the physical and virtual space. Five different systems were used to assess ergonomic data: REBA, RULA, Dtrack, HumanTech, and Delsys.

The results of this study indicate that from a static positional analysis, there are some positions (such as high reaches) that can be analyzed in both a physical and virtual environment. Tools used for static posture analysis included REBA, RULA, and Dtrack. Overall, results indicated just under 50% of actions performed in this study were deemed equivalent between both environments. The most effective tool this study found to produce the most repeatable metrics between the physical and virtual environment was HumanTech (a fluid data capture video software). A system utilizing EMG (Delsys) data was also utilized and found that even with part interaction capabilities in the virtual environment, there was almost no equivalence from the physical to virtual environment in terms of muscle activations. This research contributes new knowledge about the validity of VR for ergonomics analysis and which type of ergonomics software works best for manufacturing engineers using VR assembly simulation.

CHAPTER 1. INTRODUCTION

Virtual Reality in Manufacturing & Coupled Technology

Industry 4.0 (also known as the 4th industrial revolution) has changed the way modern manufacturing functions [1]. As technologies used in industries such as manufacturing advance, so do the methods with which we evaluate them. Virtual reality (VR) has become a key technology and is growing rapidly in implementation. As industry becomes more familiar with this technology, new ways to utilize it arise. It has been incredibly successful in areas such as streamlining designs and training processes [2].

Another common technology utilized in manufacturing is the concept of digital twins. While the exact definition of "digital twin" can differ by context, essentially a digital twin is a virtual replica of a given process/sequence that allows for predictive behavior assessment [1]. Digital twins have been rendered in a vast diverse number of software applications, and that number is still growing. VR allows us to further build on that portfolio. Coupling VR with the processing capability of digital twins opens the door for alternative assessment methods outside of the traditional process/throughput capabilities.

Ergonomics is another area that is seeing rapid technology improvement [3]. Among all assessment tools, the oldest and most widely recognized are Rapid Entire Body Assessment (REBA) [4] and Rapid Upper Limb Assessment (RULA) [5]. While these assessment tools are still used in industry, they do fall short in a few areas. Both tools are based on analyzing a static position, and although they are "rapid" forms of assessment, it takes quite a bit of time (roughly 10 minutes per stationary position) to analyze an entire assembly process. It is for this reason that new tools such as Xsens [6], Noraxon [7], and HumanTech [8] have taken a more fluid approach. These types of systems record data in real time over the full duration of the assembly process.

Assembly processes and those who perform them are active. While a majority of these tools are still based off of the high-level concepts and expectations of REBA and RULA, they provide a more wholistic and all-encompassing approach to ergonomic assessment.

There are a variety of additional tools available such as Dtrack and Delsys. While they do not perform direct ergonomic assessment, they do have the potential to aid an ergonomic assessment and provide additional data regarding movement (Dtrack) and muscle activity (EMG, Delsys) that can be utilized in unison with VR. This study sought to couple several of these emerging technologies for the purpose of more advanced ergonomic assessment. The goal was to explore how robust each of these tools might be when evaluating VR assembly vs. physical assembly. For example, would REBA, RULA, and HumanTech yield equivalent results? Would Dtrack show similar bodily movements in both conditions? Would Delsys reveal similar muscular activation in both conditions?

There appears to be an opportunity to utilize VR to perform ergonomic assessment. Considering the resources it takes to perform an ergonomic assessment (time of assessor, production time from operators, etc.), VR provides a unique opportunity in this situation. Not only does this allow the assessment process to take place in a remote location, it also allows the process to be pulled off of the production floor, which does not occupy the time of valuable skilled operators. Additional opportunities exist in areas such as new workstation design. The ability to view full workstation mockups in virtual reality and make adjustments to initial concepts could save a substantial resources, time, and in turn, money.

Research Questions

The purpose of this study was to investigate two primary research questions. Following those are related secondary research questions.

Research Question 1:

Is virtual reality a feasible substitute for physical ergonomic assessment?

Research Question 2:

When comparing body tracking systems based on computer-vision, optical markers, and EMG sensors, which provides the closest results between the physical and virtual environments?

Research Question 3:

Will younger participants have a lower task cycle time in virtual reality than older participants?

Research Question 4:

Will participants with prior VR experience perform movements in VR that more closely mirror movements in the physical world than those with less VR experience?

Research Question 5:

Will participants with prior manufacturing experience perform movements in VR that more closely mirror movements in the physical world than those with less manufacturing experience?

Research Question 6:

Will participants who are more active have a lower REBA/RULA score?

Research Question 7:

Will there be a difference between left-handed vs right-handed participants performance in the virtual environment?

Research Question 8:

Was the product easier to assemble in the physical or virtual environment based on self-reported survey results?

Research Question 9:

Did participants' rating of comfort during assembly differ in the physical vs. virtual environment?

Research Question 10:

Did participant height have an impact on ergonomic risk score result?

Structure of Thesis

This document contains five chapters. Chapter 1 covers a brief introduction to the study, followed by Chapter 2 which dives into a literature review of similar and related works. Chapter 3 covers the methodology for this study. Chapter 4 covers the data and results from this study. Finally, Chapter 5 wraps up with a discussion and conclusion of the study, including contributions, limitations, and future work.

CHAPTER 2. LITERATURE REVIEW

To explore the question of whether virtual reality is a useful replacement for ergonomic assessment, is it useful to review existing research in several domains: ergonomic assessment itself, virtual reality use in manufacturing, and other attempts to innovate the process of ergonomic assessment.

Ergonomics

Ergonomics can be defined as a scientific discipline centered around human interaction with a system to optimize human well-being and overall system performance [9]. In other words, the concept of ergonomics is centered around designing products and processes that result in safe and comfortable working conditions for the end users. As industry continues to focus on digitalization and new technology integration, new methods for ergonomic analysis are constantly changing and new systems are becoming readily available (such as wearable sensors, exoskeletons, and rapid assessment tools).

This innovative and forward-thinking focus has shifted company culture. The United States has seen an upward trend in the form of a safety movement since the 1900s with a particular impact over the last two decades. Since 2003, the recordable injury in illness rate has declined every year [10].

A study conducted by Chidinma Vivian Madueke revealed that there is a positive relationship between innovative culture and employee commitment [11]. Ergonomics have the ability to drastically impact time, cost and quality [12]. Placing employees in unsafe environments can have a multitude of repercussions on both a financial and ethical level.

While company culture shift has played a large influence on ergonomic innovation, the sheer number of incidents and financial statistics are enough to drive this movement as well.

According to the National Safety Council in 2020 the average cost of a work-related injury requiring medical consultation was $44,000 [13]. Additionally, according to the U.S. Bureau of Labor Statistics, 2021 presented 2,607,900 recordable injury cases [14]. Regardless of the motivator, companies in general are taking a more proactive approach to ergonomics.

Ergonomics has benefitted in the past decade from major improvements in technological capabilities. The use of new technologies and different simulation models in manufacturing is rapidly growing [15]. For example, Amazon Web Services conducted a study utilizing a wearable 3-layer sensor vest to implement a flexible and all-encompassing ergonomic assessment. This system utilized both inertial measurement units as well as electrocardiogram readings taken via Bluetooth. Two conditions were monitored for a between-subjects analysis focusing on white collar work risk vs blue collar work risk [16]. This study aimed to target manufacturing environments specifically, with the intent of comparing different ergonomic assessment tools, as opposed to one form of assessment. Similarly, the current study focuses on comparing multiple ergonomic assessment tools and the use of a virtual reality digital twin for manufacturing assembly.

Virtual Reality in Manufacturing

Virtual reality is defined as a technology that that enables the creation and use of computer-generated three-dimensional environments [15]. Virtual reality environments are powerful tools that allow the user to indulge in a fully immersive experience. This environment allows the user to fully experience an alternative reality while interacting with different parts and simulating actions. Cost reduction is always at the forefront of any successful business mind, and technology integration has provided unique opportunities to do just that. Virtual manufacturing (VM) is a large industry topic focused on improving workstation design, task planning, and reduction of inefficiencies [17]. Specifically, VM focuses on improving system design, and manufacturing ergonomics.

One example of virtual reality utilization is in an industrial study that was performed on a tractor assembly line [15]. The scope of this study involved one of 15 stations and simulated different sequences of events and performed several scenarios including different bottlenecks. There was a large emphasis put on utilizing the immersive simulation from a collaborative standpoint. Groups of 5-10 individuals were able to work collaboratively to alter outcomes of each simulation and reported that they were quickly able to comprehend details of the simulated activity. While remote collaborative work is a byproduct of virtual reality integration in general, this study attempted to prove the validity of ergonomic assessment in a virtual environment, similarly to the current study.

Coupled Technology

A study titled “On the use of Virtual Reality for a human-centered workplace design” took a unique approach to the use of virtual reality in tandem with ergonomics [18]. Centered around the assembly of automobiles, individuals performed simulated assembly steps for the same activity in two different types of vehicles by means of inertial motion capture. These motions were tracked and replicated in a virtual workspace for future analysis. The study conducted in this paper aimed to take a more direct approach to the assembly capability. Instead of simulating assembly steps, part interaction was enabled by the virtual workspace, allowing for a more accurate representation of the assembly movements and part interaction.

Another study conducted by Margherita Peruzzini took a new approach to ergonomic assessment and virtual reality. This research consisted of utilizing CAD models representative of a factory layout to create a simulated rendering in Unity, a 3D simulation engine. In this virtual reality rendering, a body-tracker-based ergonomic tracking system called Xsens [6] was coupled with a Leap Motion package to capture and record user movements. Participants completed two different assembly tasks centered around tractor assembly. Additionally, this study compared the virtual manufacturing environment assessment to that of desktop-based ergonomic assessment software, JACK. JACK is a software that utilizes a virtual mannequin consisting of 26 anthropometric configurable dimensions to ensure different size variants in the population can safely and effectively utilize a workspace. The study concluded that the virtual manufacturing procedure was in fact validated on the industrial assembly case, and when compared to the desktop-based simulation model, the immersive headset approach to virtual reality proved to be more powerful.

While this previous research supports the overall goal of this research, this current study takes a somewhat different approach. While JACK is a very capable and widely used software and can perform fluid ergonomic analysis, its primary scope is to assess static postures from a 3D analysis perspective. When coupled with an external software (such as Xsens or Kinect), this does allow for the collection of continuous positional data. Also, while JACK is a very capable software, it does require a significant anthropometric understanding. The model with JACK has 26 manipulatable dimensions. Users must understand the broad range of variation in population data. The configurability of this software is powerful for experts in the field, but there is a large learning curve associated with it for those who are not. Additionally, the need to pair this software with an external body tracking system to truly capture an accurate capture of human motion provides another learning hurdle.

An alternative approach, used by the current study, is HumanTech. HumanTech simply requires the user to record and upload a video of a person completing the assembly process, and HumanTech generates an easily understandable ergonomic assessment, providing fluid data capture without the need to pair with an external system. While this is one successful combination of virtual reality and ergonomics, this study intends to take it a step further. A wide range of different ergonomic evaluation tools are available, and their compatibility with virtual reality has yet to be analyzed. Finally, while ergonomics can be evaluated from a fluid data capture standpoint, static positional analysis is also a common assessment method. The current study seeks to evaluate both.

A study titled “Virtual Reality: Its Usefulness for Ergonomic Analysis” similarity sought to generate a physical and virtual task to address if virtual reality is a suitable tool for ergonomic analysis [19]. Subjects performed a palletizing task in two environments, and the authors concluded that it was in fact a viable substitute when neglecting velocities and accelerations. This assessment methodology has a bit of a different approach in terms of ergonomic tools, as they utilized a lumbar motion monitor. This is an exoskeleton type suit that captures 3D movement of the spine. Additionally, motion tracker balls were utilized to generate a 3D rendering of the subject. Counterbalancing was not applied to this study, as all participants began in the virtual environment. There was a large emphasis placed on trunk position/analysis focusing on musculoskeletal disorders (MSD). MSDs accounted for 55.4% of private industry ER visits in 2019 [20]. MSD is a large focus area in ergonomics; however, it is not the only one. Tasks such as repetitive motion, neck position, shoulder position, etc. all need consideration when completing a thorough ergonomic analysis. The current study will integrate a full body ergonomic assessment (REBA and HumanTech), as well as attempt to fill some gaps regarding different types of ergonomic assessment tools.

A systematic literature review conducted by Silva and Winkler in 2020 provides an all-encompassing overview regarding virtual reality’s ability to support ergonomic analysis [12]. It described different resources from both the technology side and the ergonomic side of evaluation. This review also offers a plethora of examples of potential tools to couple around this methodology such as REBA (Rapid Entire Body Assessment), RULA (Rapid Upper Limb Assessment), OWAS (Ovako's Work Posture Analysis System), DHM (Digital Human Models), and HCD (Human Centered Design), and others. It explicitly points out the shortcoming that a majority of VR/ergonomic coupled assessments are performed in the automotive industry. Large equipment manufacturing (such as automotive) does provide a large opportunity for ergonomic analysis, as designing for process assembly is critical in this industry. For example, operators need to have room inside automotive frames to ensure they can assemble components correctly the frame, and this requirement often creates awkward positions due to the nature of the product. Even the study mentioned prior [19] focused on a larger lift/lower type action. Large process movements are easy to capture but are only a small part of ergonomics. This study focuses on manufacturing at an assembly workbench, which is relevant and applicable to a wide range of manufacturing industries.

As technology continues to develop in both the virtual reality and ergonomic field, there are a limitless number of assessments to be performed to discover feasible combinations of the two disciplines, as well as under what circumstances these systems need to operate. Different processes may require different types of assessment tools. This study aims to identify a few of those combinations and caveats.

CHAPTER 3. METHODOLOGY

Product Development

This study required participants to assemble a product in both a physical and virtual environment. A custom product was fabricated to eliminate any previous experience or knowledge interfering with the assembly process. For example, if the assembly had been LEGO based, a participant who avidly assembled LEGOs would have a competitive advantage over a participant who utilized LEGOs less frequently. Presenting an original product was intended to create the same experience for each participant, which led to the development of the Portable Ergonomic Assessment Tool (PEAT). Figure 1 displays the first design iteration for PEAT, consisting of a main cube-like base on to which multiple parts could be assembled.

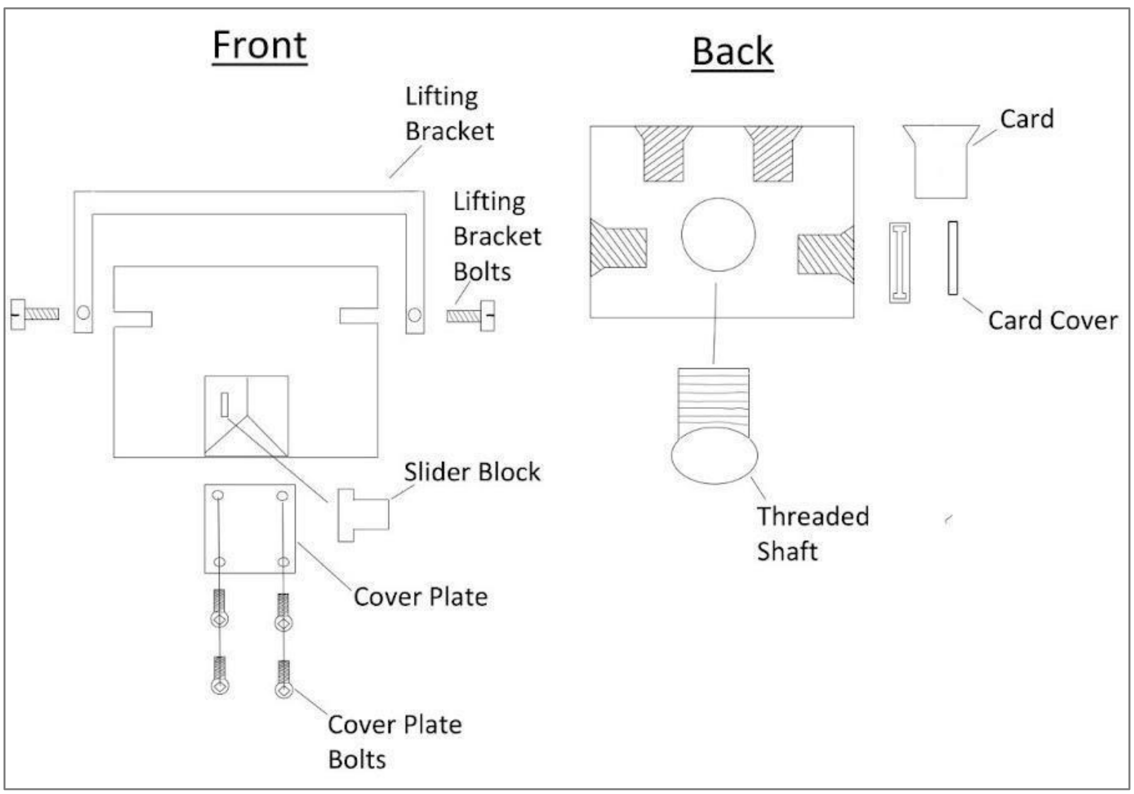


Figure 1: Initial PEAT concept

Figure 2 displays the final PEAT assembly. The right side of the figure depicts physical version of PEAT while the left side of the figure depicts its virtual counterpart. PEAT consists of 12 total parts including the large main base, and 11 smaller components to be assembled into it (see APPENDIX D: PEAT BOM for full bill of materials). All components with exception to the four cover plate screws were 3D printed. Figure 3 displays the PEAT assembly exploded view of the part. Here it is visible how all parts are assembled relative to one another.

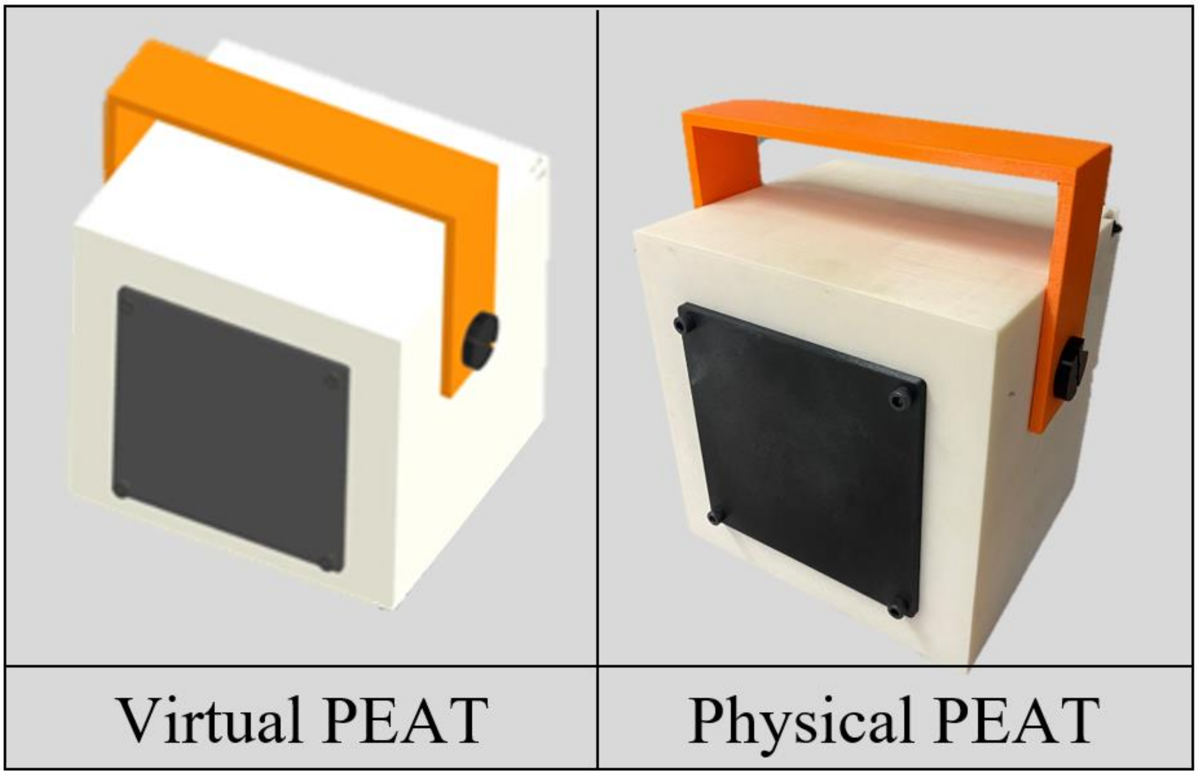


Figure 2: Virtual vs Physical PEAT Final Design

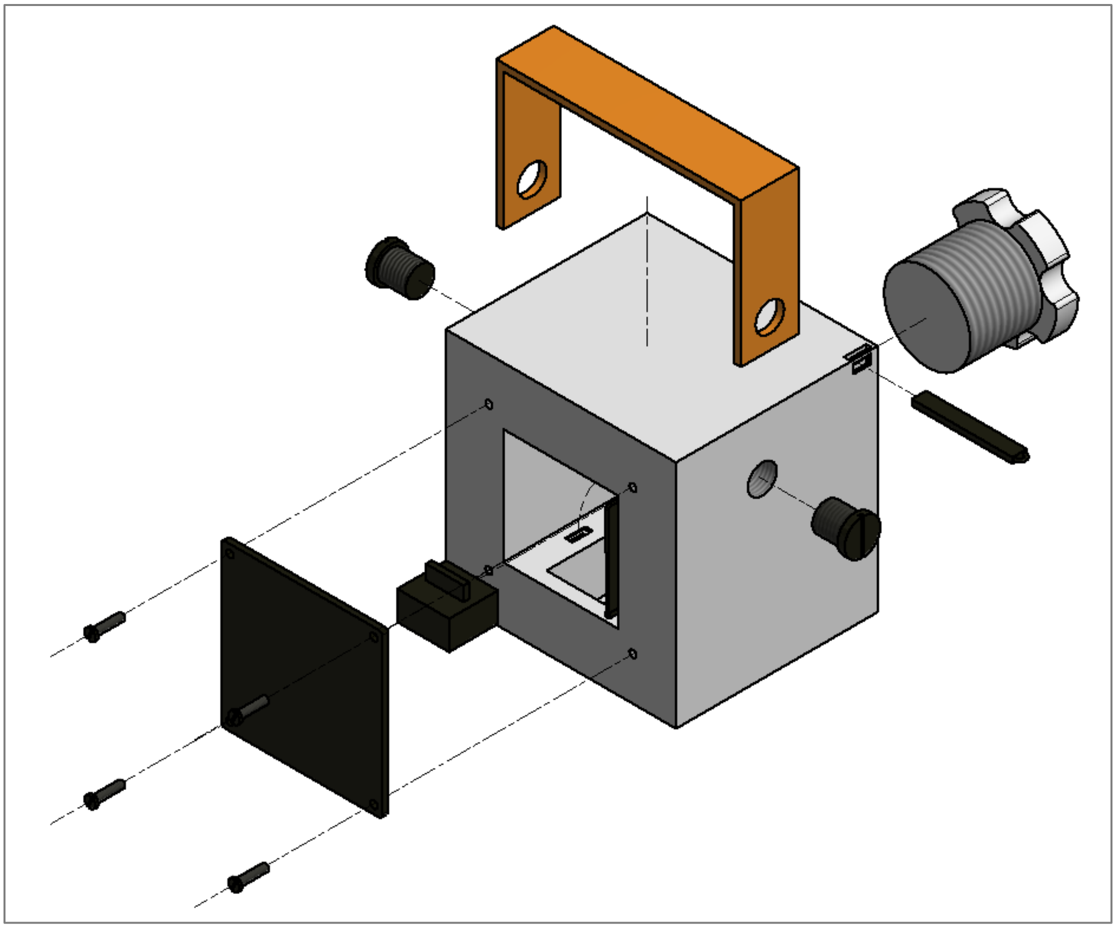


Figure 3: PEAT assembly exploded view.

It was quickly determined following the finalization of PEAT that there would be some subjectivity regarding the part orientation during the assembly process across participants. For this reason, an assembly fixture was quickly developed. This would assist the participant in the part rotation process and create a more repeatable part manipulation during data collection. Figure 4 depicts the assembly fixture.

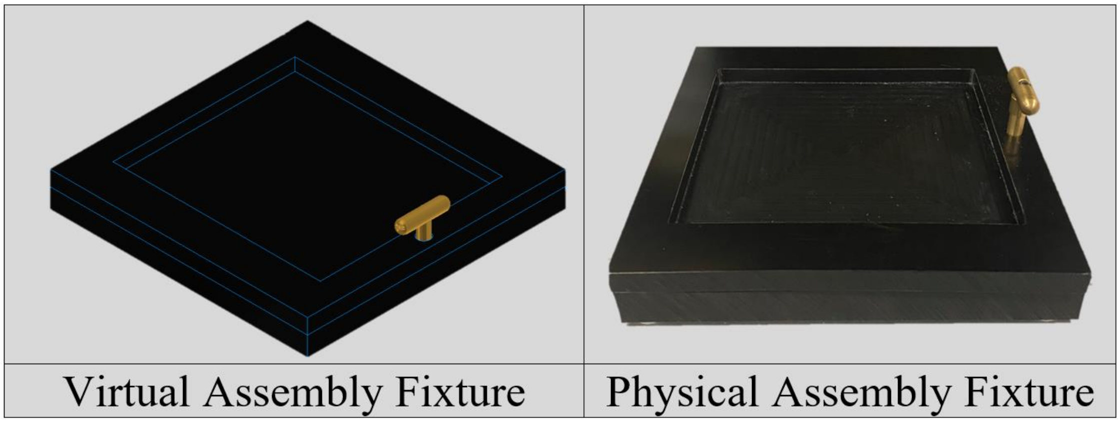


Figure 4: Virtual vs Physical Assembly Fixture

A standard work process was developed to ensure repeatability across participants. Figure 5 displays the standard work process and documentation provided to the participant for reference.

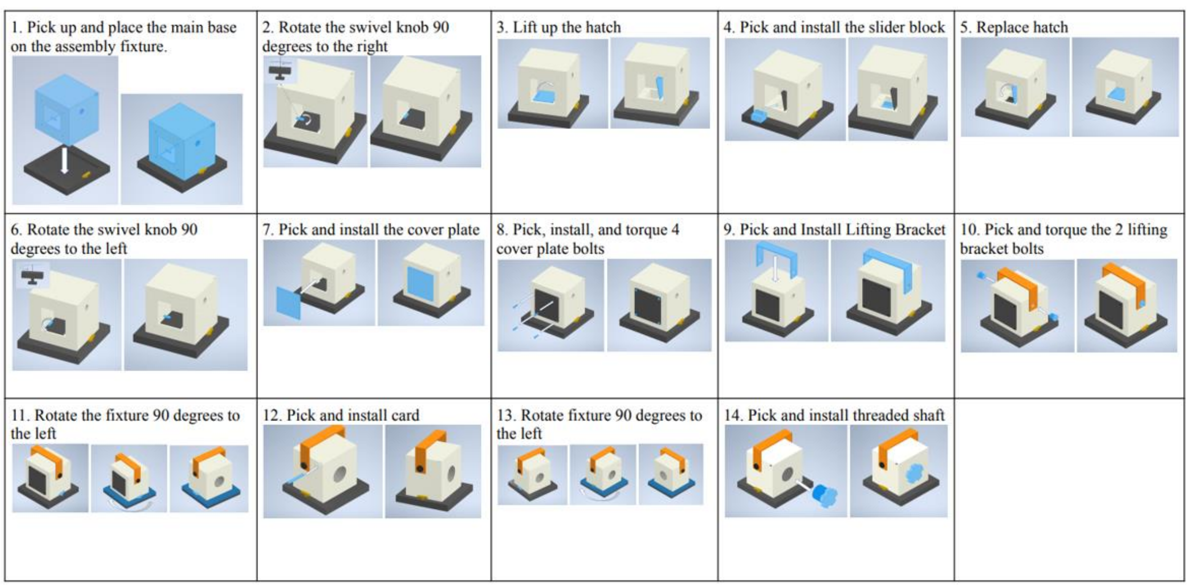


Figure 5: PEAT standard work process

Environment Development

Physical Environment

The PEAT physical environment was heavily influenced by the goal to reflect a realistic manufacturing assembly workstation. A standing workbench was set at an industry standard height of 36”. This allowed for the recommended working surface height of 42-44”, after considering the added height from the assembly fixture (1”), and the height of PEAT (10”, though a majority of the assembly takes place in the center of PEAT, around 5-8”) [21]. Three shelves were utilized for bin/part storage in an attempt to assess a high, medium, and low reach height. The assembly fixture was secured to the table using a double-sided adhesive. Each bin was allocated a part and corresponding label. A copy of the standard work was posted for the participant to reference during the study. Finally, a small side table was placed next to the workbench to implement a lift and lower movement. Figure 6 displays the final physical environment.

Figure 6: Physical environment

Virtual Environment

Once a physical workspace and workbench were established, the space was replicated and rendered in a virtual environment to create a digital twin of the workspace [1]. The entire space was rendered in 3D CAD software (Inventor Pro), and then integrated into an interactive Unity environment. Images of the workbench table, wooden door, side panels, and floor were taken and developed into virtual materials to keep the rendering as accurate as possible. This approach created a full immersive experience for the participant. Figure 7 displays the virtual environment rendering.

Figure 7: Virtual environment

Once the base model was completed, SteamVR plugins, as well as Unity's VRTK (Virtual Reality Toolkit), allowed for the interactive object programming. This interactive programming allowed for the interaction and assembly of parts as well as the application of physics properties, allowing all objects to succumb to the forces of gravity if dropped. This study utilized a Valve Index HMD and controller configuration, as shown in Figure 8. The Valve Index contains dual 1440x1600 LCDs with a framerate of up to 144Hz. This headset has an adjustable inter-pupillary distance (IPD) ranging between 58-70mm, allowing for a customizable clear focus for each wearer. It also contains built in audio, as well as 960x960 pixels [22]. This system was selected for a variety of reasons. First, it has high rendering capability compared with other HMDs. Additionally, this study strayed away from the Oculus (Meta Quest Series) due to the fact that when programming the headset interaction in Unity, a standard "XR Plugin" is compatible with a wide range of different systems. Due to Meta's unique and specialized programming, there are only a select few packages compatible with its software. Additionally, this headset allowed the researcher to adjust the interpupillary distance (IPD) of each participant. This brought the headset into focus for all participants.

Figure 8: Valve Index headset
Source: https://www.amazon.com/Valve-Index-VR-Full-Kit-PC/dp/B07VPRVBFF

The controller was programmed to utilize the “Finger Tracking Grip Force Sensor” to emulate grabbing a part (see Figure 9). This required the participant to squeeze the controller to interact with the part, as opposed to pushing a button.

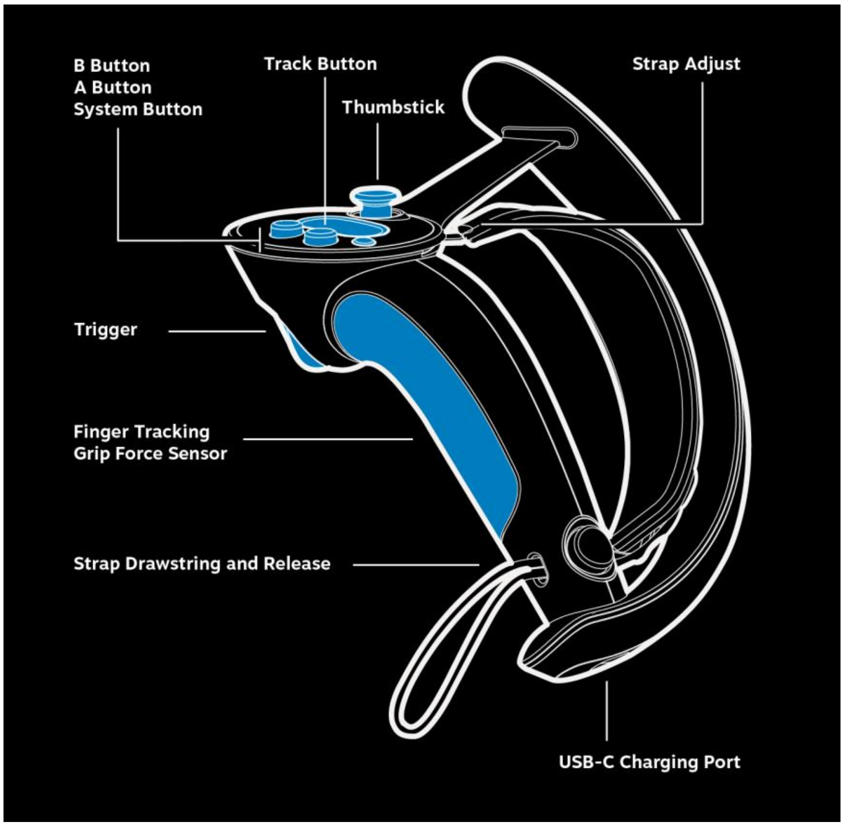


Figure 9: Valve index controller configuration
Source: https://steamuserimages-a.akamaihd.net/ugc/927060754649206815/95290F2C2D3ABF7CBA0433FBEC2CF38E472ADFD5/

Virtual reality was selected as the environment tool of choice (as opposed to augmented reality), for a variety of reasons. The first being its rendering capacity/capability. Augmented Reality (AR) headsets (such as the Microsoft HoloLens) are stand alone and have a limited rendering capability. This rendering ability is determined through a process called tessellation. Tessellation is the process of mapping a surface via small triangles to create a surface profile. In essence, this creates triangular pixels if you will. The more tessellation a rendering has, the higher resolution and more detail it contains. That said from an industry standpoint, a single station of an assembly line can come in up to around 1,000,000 triangles. This station would need to be simplified down enough that the headset is able to render it without crashing. Through trail and error, it was discovered that the HoloLens has a rendering limit of ~250,000 triangles. When simplifying files, any internal components must be deleted (nuts bolts, etc), while all exterior components must be rendered as blocks or cylinders. Figure 10 displays an example of this simplification. With this in mind, a lot of detail is lost for each assembly station. It is common for assembly lines to have 10 or more stations in its entirety, making a full line rendering nearly impossible in AR.

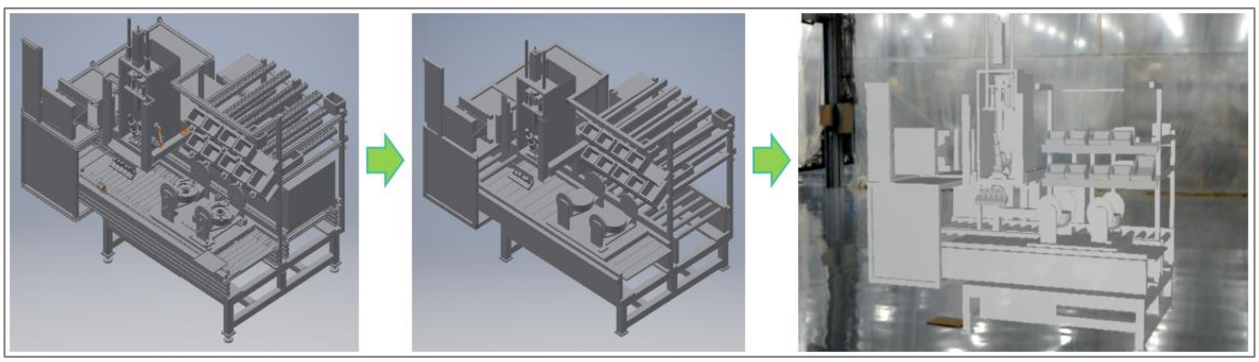


Figure 10: Industry example of HoloLens simplification of a single assembly station

Another justification for the selection of VR is the anchoring ability of AR. An object can be placed on the ground, however as one moves around to interact with the station (especially when the station is at the upper limit of its rendering capability), the station tends to shake a bit and move around. Additionally, there is no real understanding of ground level. The headset will tessellate and map a boundary space in which the object is to be placed, however the user still has the ability to place the object past that boundary. Conservatively, this often means stations will tend to float a bit. Additionally, AR struggles with reflective surfaces (such as the newly finished floor in Figure 10). This proves difficult for a variety of different assembly plants.

A small pointer dot was programmed to be associated with each controller to assist the participant in interaction with smaller components. Figure 11 displays the participant's view of the controllers. One dot was programmed directly in front of the controller, while the other was programmed 90 degrees to the right. The intent behind this orientation was to allow the participant to grab objects inward instead of directly in front, in hopes of creating more natural movement.

Figure 11: Virtual environment interactive controller point location. Left controller controlled the red pointer dot at right of it. Right controller controlled the red pointer dot in front of it.

Tracking Systems and Assessment Tools

This study utilized four different methods of ergonomic and position analysis: REBA/RULA, HumanTech, Dtrack, and Delsys, each of which is described below.

REBA/RULA was intended to justify how both the physical and virtual environments compare ergonomically to one another. While the main objective of this study was to analyze postures, an outstanding question remained: will people make the same movements with their body while assembling a product in a virtual environment as they do in a physical environment, and are there other tools that can be used to capture this variation? The other three tracking systems came into play to answer this question. Below are brief descriptions of each tool's functionality and contribution to the study.

REBA

REBA is an acronym that stands for Rapid Entire Body Assessment [4]. This tool was developed by a team of ergonomists with the intention of allowing for a quick assessment of musculoskeletal risk for a given task with minimal equipment. Originally designed for use in the unpredictable working conditions of healthcare, this worksheet-based tool encompasses both the upper and lower portions of the musculoskeletal system [4]. An evaluator fills out a worksheet for a given static position of an individual. At the end of the form, a total risk score is calculated with a range of 1-15 that indicates if the process or task requires intervention based on risk; higher numbers represent more risk. It is important to note that this assessment does not take duration of task into consideration, as it is concerned with a single stationary position in time. While many other ergonomic assessment tools have been developed, many are based on this tool. REBA allowed the researchers to address different risk levels associated with full body postures throughout the assembly process. While this assembly was primarily based on the upper body, virtual reality could play a large role in affecting a participant’s overall body posture. Figure 12 below shows the REBA assessment tool form. Figure 13 displays the levels of musculoskeletal disorder (MSD) risk calculated from the REBA assessment.

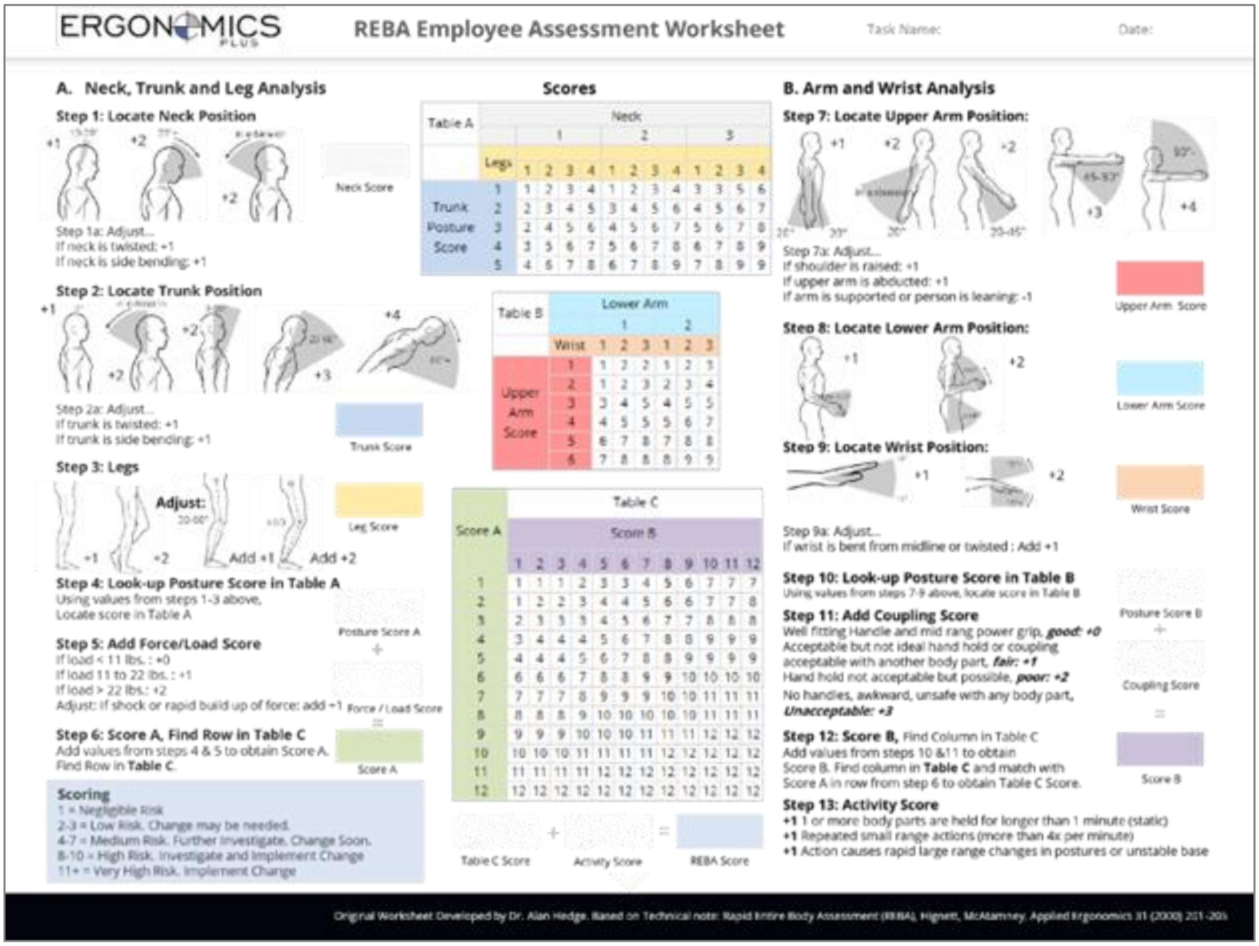


Figure 12: REBA assessment form [23]

Score	Level of MSD Risk
1	negligible risk, no action required
2-3	low risk, change may be needed
4-7	medium risk, further investigation, change soon
8-10	high risk, investigate and implement change
11+	very high risk, implement change

Figure 13: REBA risk levels for musculoskeletal disorder
Source: https://ergo-plus.com/wp-content/uploads/rapid-entire-body-assessment-reba-2.png?x40319

RULA

RULA is an acronym that stands for Rapid Upper Limb Assessment [5]. Similar to REBA, this tool was developed with the intention of allowing for a quick assessment of musculoskeletal risk for a given task, but this tool has an emphasis on the upper body. At the end of the form, a total risk score with a range of 1-7 is calculated, indicating if the process or task requires intervention based on repetitive risk. This assessment also does not factor in duration of the task. While REBA does encompass the entire body, RULA allows the evaluator a more detailed analysis for assembly processes that are largely upper body in nature. Because PEAT was assembled at a stationary assembly workbench while standing, RULA was a relevant assessment tool for this study. Figure 14 below shows the REBA assessment tool form. Figure 15 displays the levels of MSD risk calculated from the REBA assessment.

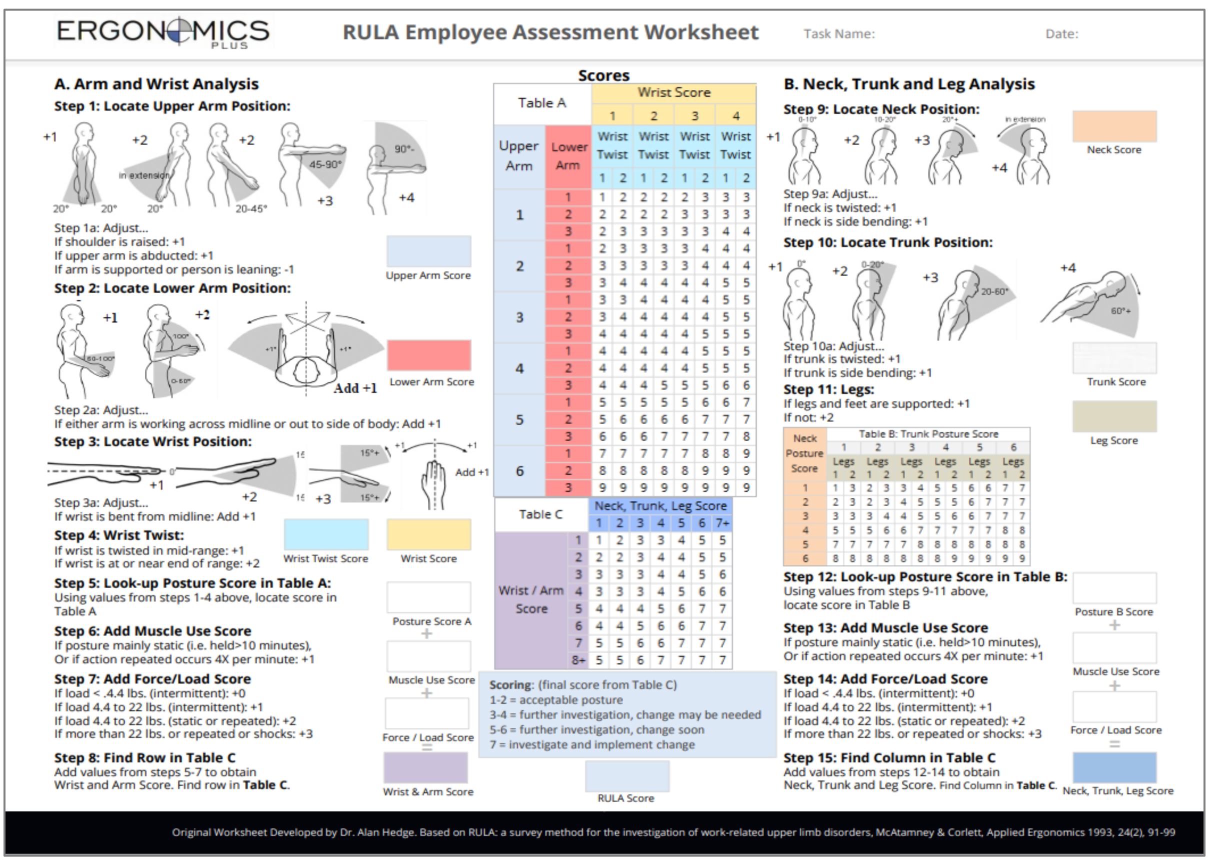


Figure 14: RULA assessment form [24]

Score	Level of MSD Risk
1-2	neglibible risk, no action required
3-4	low risk, change may be needed
5-6	medium risk, further investigation, change soon
6+	very high risk, implement change now

Figure 15: RULA risk levels for musculoskeletal disorder
Source: https://ergo-plus.com/wp-content/uploads/rapid-upper-limb-assessment-rula-2.png?x40319

HumanTech

HumanTech (developed by VelocityEHS) is a camera based, AI-based tracking system, that performs a skeletal overlay on video in post processing, however unlike REBA/RULA, allows the evaluator to fluidly record and capture data [8]. It is scaled a bit differently (as shown in Figure 16), but it essentially automates the REBA/RULA process. A video of the operator performing the task in question is recorded and uploaded to the software. In roughly 20 minutes, the software provides a risk assessment that can be played back with a skeletal overlay. In real time, evaluators can watch which areas of the body are experiencing risk at a given time. The assessment is broken down with scores for 9 different areas of the body, e.g., the left and right shoulders or the neck, which ranges from 0 to 7 or higher, with higher values indicating greater ergonomic risk. HumanTech also offers an overall Advanced Tool Priority Score, which measures a summation of all body area scores which ranges from 0 to 50 or higher, with higher values also indicating greater ergonomic risk. Although scaled a bit differently, the results are presented in the same format as REBA and RULA. This score is the summation of risk from all portions of the body. Figure 17 displays a completed risk assessment. HumanTech has become a widely recognized and reputable tool in industry. Not only does it make ergonomic assessment accessible and efficient, but it allows experienced ergonomists access to finite details of the analysis (such as grip styles, forces, back end development tools, etc.).

Advanced Tool Priority Score				
Lower 0 - 9	Low 10 - 19	Moderate 20 - 29	High 30 - 49	Higher 50+
Body Area Score				
Lower 0 - 1	Low 2	Moderate 3	High 4 - 6	Higher 7+

Figure 16: HumanTech risk scores
Source: HumanTech VelocityEHS job assessment info screen

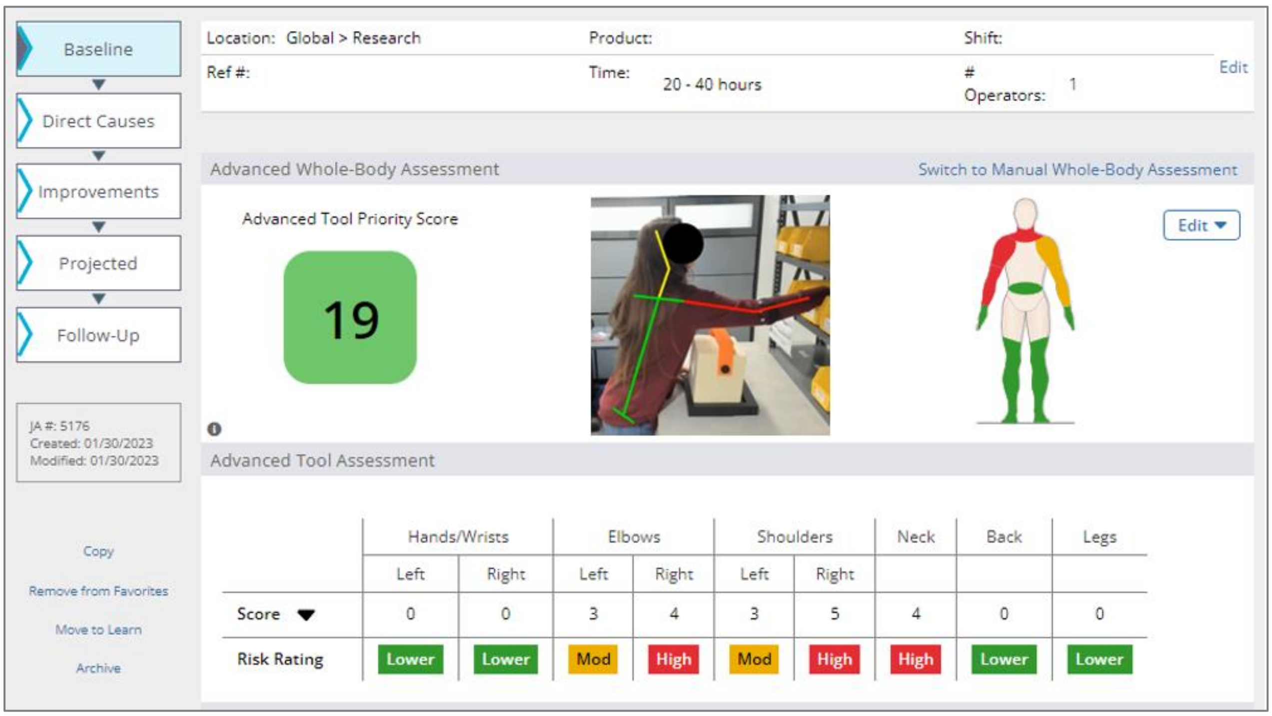


Figure 17: HumanTech risk assessment
Source: HumanTech VelocityEHS job assessment software result screen

Delsys

Delsys Trigno is a wireless electromyography (EMG) and Inertial measurement unit (IMU) based tracking system. While this system is capable of utilizing both functionalities, this study only utilized the EMG capabilities, as it was centered around tracking muscle activation. This system has a maximum sampling rate of 4370 sa/second, an EMG input range of 11-22mV, and a 40m operating range [25]. While a variety of sensors are available/compatible with this system, this study utilized the Trigno Avanti Sensor, as it is completely wireless, easy to connect, and has color-coded visual feedback regarding connection status. Figure 18 displays the Delsys Trigno Research case, the Trigno Avanti Sensor, as well as an image of the EMGWorks software utilized to capture and collect the EMG data.

Figure 18: Delsys Trigno System, Sensor, and Interface
Sources: https://images.app.goo.gl/KTsAtTD16htypi8z7
https://images.app.goo.gl/cmqMbQmVTkEtHAb96
https://images.app.goo.gl/wVxESWxiZqprQWaR8

ART Dtrack

Dtrack is a tool developed by Advanced Realtime Tracking (ART). Dtrack is a camera-based reflective motion tracker ball system. Custom 3D printed individual components (as shown in Figure 19) were developed to hold the reflective tracker balls. Each unique holder allowed the system to recognize its set of motion tracker balls as being an individual object. With a maximum of 4 body IDs allowed by the system, this study targeted head tracking via glasses, the right and left arms just below the elbows, and the sternum. The glasses were selected to provide results for head tracking, left and right arms to track arm movement during the assembly process. Finally, the sternum was selected with the intent of providing a “centering” point for each participant. In other words, with frequent arm or head movement, the trunk of the body may remain more stationary and centered, and this study wanted to capture that.

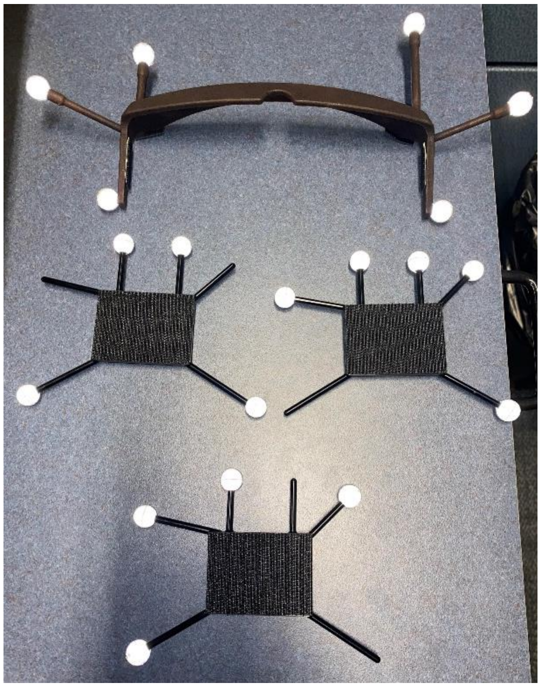


Figure 19: 3D printed Dtrack motion ball plates

It is important to note that for the physical environment, participants wore the head tracking sensors on a pair of empty glasses frames, while in the virtual environment, the head tracking sensors were swapped to the virtual reality headset as displayed in Table 1.

Table 1: Physical vs Virtual Dtrack Head Tracking

Physical Environment Head Tracking	Virtual Environment Head Tracking
	

Finally, four cameras were mounted on an 80/20 structure above the assembly workbench to track the motion tracker balls location, as shown in Figure 20.

Figure 20: ART Dtrack camera placement

Experimental Design

Power Analysis

A sample of 10 trial participants were run (exclusionary to the 65 total participants who participated in this study) in order to calculate a power analysis. This analysis provided the minimum required sample size for this study. Mintab was utilized for this assessment. As displayed in Table 2 and Table 3, the average REBA/RULA for the first 10 participants in the physical environment was 3.63 while the physical environment had an average score of 3.51 equating to a total difference of 0.125 in score on average. The cumulative standard deviation for the difference in these two assessments was 0.36 as shown in Table 4.

Table 2: First 10 analysis REBA assessment results for power analysis for the 8 major steps of assembly

REBA Assessment Position	Mean		Std. Dev.		Min		Max		S1-S2
	P	V	P	V	P	V	P	V	
Housing Pick	5.10	4.90	1.10	.088	4	4	7	7	0.22
Housing Install	1.90	2.80	1.10	0.92	1	1	4	4	0.18
Slider Block Install	2.40	2.70	1.26	0.67	1	2	5	4	0.59
Top Left Bin Pick	5.60	5.10	0.97	1.38	4	4	7	8	-0.40
Fixture Rotation	2.30	2.60	0.82	0.84	1	1	3	4	-0.02
Bottom Right Bin Pick	5.00	4.10	1.63	0.88	3	3	8	5	0.76
Center Middle Bin Pick	4.60	4.40	0.51	1.07	4	2	5	6	-0.56
Threaded Shaft	2.40	3.20	0.97	0.63	1	2	4	4	0.33

Table 3: First 10 analysis RULA assessment results for power analysis (and summary statistics for power analysis calculations)

RULA Assessment Position	Mean		Std. Dev.		Min		Max		S1-S2
	P	V	P	V	P	V	P	V	
Housing Pick	5.40	4.00	1.43	0.82	3	3	7	5	0.61
Housing Install	3.60	3.30	0.70	0.82	2	1	4	4	-0.12
Slider Block Install	3.10	3.10	0.32	0.32	3	3	4	4	0.00
Top Left Bin Pick	3.20	3.20	0.42	0.42	3	3	4	4	0.00
Fixture Rotation	3.00	3.30	0.00	0.67	3	3	3	5	-0.67

Table 3 Continued

RULA Assessment Position	Mean		Std. Dev.		Min		Max		S1-S2
	P	V	P	V	P	V	P	V	
Bottom Right Bin Pick	4.00	3.20	0.47	0.42	3	3	5	4	0.05
Center Middle Bin Pick	3.30	3.00	0.67	0	3	3	5	3	0.67
Threaded Shaft	3.20	3.50	0.42	1.27	3	3	4	7	-0.85

Table 4: First 10 analysis summary statistics

Statistics	REBA	RULA	Differences
Average Score	3.545	3.433	0.113
Standard Deviation	1.574	1.272	0.302

The Minitab “Power and Sample Size for Equivalence Test with Paired Data” requires the following inputs: lower limit, upper limit, differences (within the limits), power value, and standard deviation of paired differences. These terms are defined and outlined in Minitab’s webpage titled “Enter your data for Power and Sample Size for Equivalence Test with Paired Data” [26]. Table 5 displays the inputs utilized for the first 10 analysis for power analysis, which resulted in a required sample size of 53 participants as displayed in Table 7. Figure 21 displays the power curve for equivalence test with paired data generated by Minitab for this power analysis. The upper and lower equivalence limits were set based on the idea that it takes an average risk score change of 2 points to result in a risk level change (see REBA/RULA Bounds section for additional details). This study was able to slightly exceed that value with a total of 65 participants.

Table 5: Minitab power analysis inputs

Input Description	Input
Hypothesis about	Test mean - reference mean (difference)
Alternative hypothesis	Lower limit < test mean - reference mean < upper limit
Lower limit	0
Upper limit	2
Differences (within the limits)	0.125
Power value	0.8
Standard deviation of paired differences	0.36

Table 6: Method results from Minitab power analysis

Method	
Power for difference	Test mean- reference mean
Null hypothesis	Difference <= 0 or Difference >= 2
Alternative hypothesis	0 < Difference < 2
α level	0.05
Assumed standard deviation of paired differences = .36	

Table 7: Minitab power analysis results

Results			
Difference	**Sample Size**	**Target Power**	**Actual Power**
0.125	53	0.8	0.802296

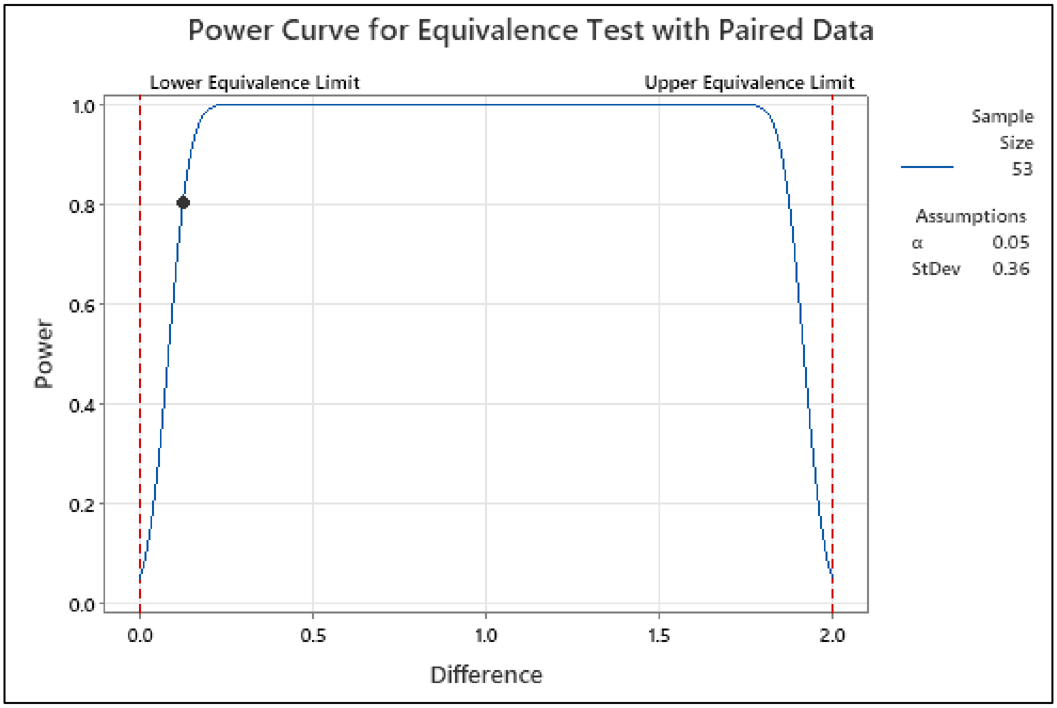


Figure 21: Minitab generated power curve for equivalence test with paired data

Experimental Design Flowchart

Figure 22 below displays a flowchart of the PEAT study experimental design. Following consent forms, participants took a pre-study survey and mental rotation test. They were then provided a 10-minute training regarding how to assemble PEAT. Sensors for all systems were then attached to the participant. Counterbalancing was applied to this study to minimize the influence of seeing one environment vs the other. Odd numbered participants would assemble in the physical environment first, while even numbered participants would assemble in the virtual environment first. Each participant assembled PEAT in both environments to perform a within-subjects analysis. Following each assembly, participants took a brief 30-second survey regarding their ergonomic discomfort in each environment. Finally, once both assemblies were complete, participants took a post study survey regarding their overall experience, which lasted typically 1 minute. Each of these steps are described further below.

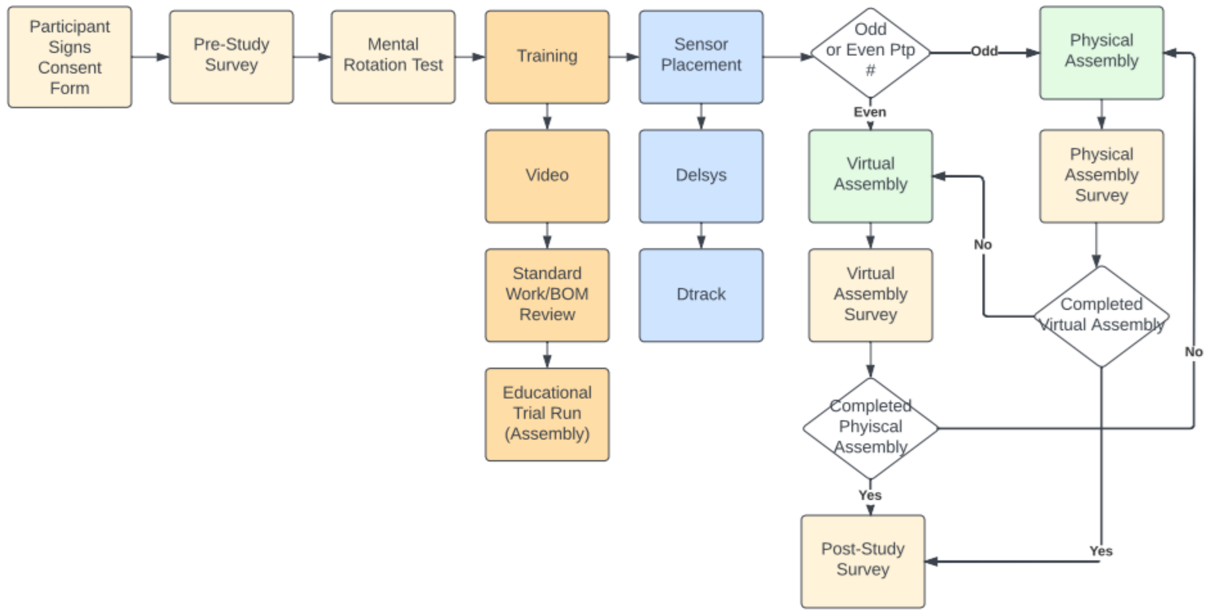


Figure 22: PEAT study experimental design flow

Pre-Study Survey

Upon arrival, participants partook in a pre-study survey. The intent of the pre-study survey was to gain information regarding the participants' demographics, as well as their amount of exposure to virtual reality and to manufacturing to investigate potential correlation in performance.

Mental Rotation Test

Following the pre-study survey, participants completed a mental rotation test[27]. This was a test of the participants ability to view a 3D object with the objective of selecting the two of four additional matching objects at different orientations. Scores were reflective of both correct and incorrect answers. Figure 23 displays the first of 20 questions on the mental rotation test.

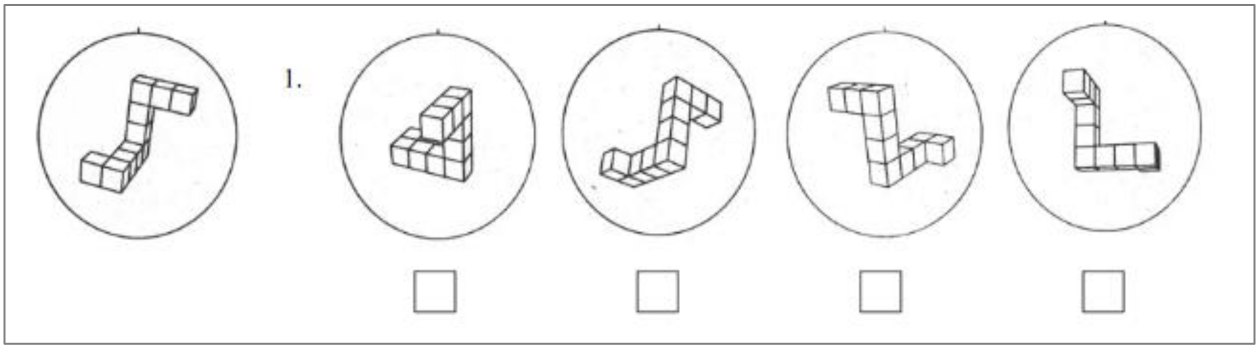


Figure 23: Mental rotation test example question [27]

Training

Next, participants would begin the training portion of the experiment. They were provided a brief verbal overview of PEAT and how the assembly fixture worked. A short 3-minute training video was provided. This video included a walkthrough of how to assemble PEAT, as well as a virtual rendering of the assembly taking place. The short virtual assembly video provided a second opportunity to view the process in hopes of assisting with knowledge retention. A copy of the standard work document (see Figure 5) was provided throughout the physical assembly for viewing as well. Finally, participants would begin their first physical interaction with PEAT partaking in an educational trial run. A video recording was taken simply to extract a cycle time.

Experiment Trial Setup

Once participants were comfortable with the assembly process, all sensors and recording devices were applied. Beginning with Delsys, ten Delsys Trigno wireless sensors were applied to each participant, utilizing double-sided sticky tape, as well as medical grade bandage tape to ensure contact throughout the experiment. These sensors were strategically placed to focus on upper body utilization only, as assembly took place at a stationary standing work bench. These sensors were also applied first, as they required direct contact with the participant's skin. Figure 24 and Table 8 display the placement of the Delsys sensors, as well as the specific muscles they are targeting.

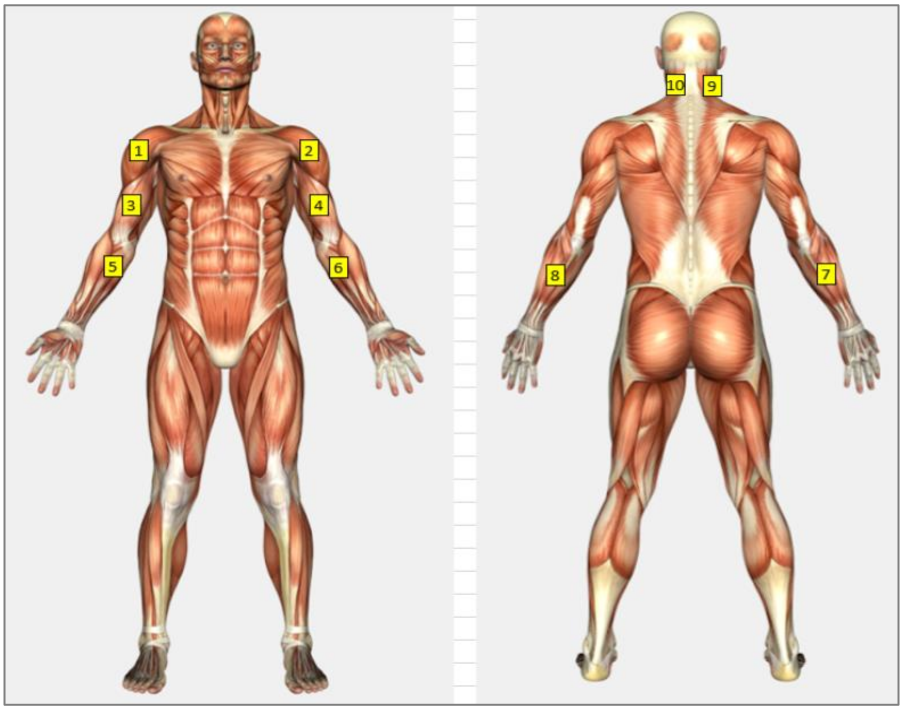


Figure 24: Delsys sensor placement
Image Adapted from Delsys EMGWorks software version 4-8-0 (yellow location tags added to indicate sensor placement for this study)

Table 8: Delsys Sensor Placement Reference Table

Sensor #	Muscle Name	Description
1	R Deltoid	Right Shoulder
2	L Deltoid	Left Shoulder
3	R Biceps Brachi	Right Upper Inner Arm
4	L Biceps Prachi	Left Upper Inner Arm
5	R Flexor Carpi Radialis	Right Lower Inner Arm
6	L Flexor Carpi Radialis	Left Lower Inner Arm
7	R Extensor Digitorum	Right Lower Outer Arm
8	L Extensor Digitorum	Left Lower Outer Arm
9	R Trapezius Upper Fibers	Right Back of Neck
10	L Trapezius Upper Fibers	Left Back of Neck

Following the Delsys sensor placement, the ART Dtrack sensors were then applied. These sensors were placed on the front of the body and on the tops of the arms, allowing the 4 cameras mounted above the workbench to track their position. Utilizing the custom 3D printed platforms/holders, sensor groupings were applied via Velcro straps to participants left and right arms, across the participants sternum (using a Velcro cross body strap), and head (using a pair of empty frame glasses). Figure 25 and Table 9 display locations for ART Dtrack sensors.

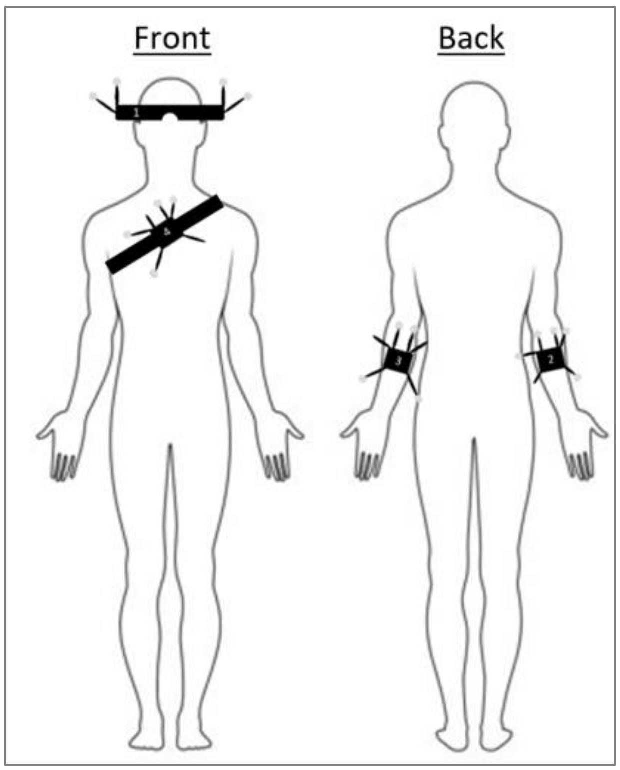


Figure 25: ART Dtrack sensor placement

Table 9: ART Dtrack sensor placement reference table

Sensor #	Location
1	Glasses
2	Right Arm
3	Left Arm
4	Sternum

Physical Assembly

For simplicity, we will follow the process flow for an odd numbered participant (physical assembly first). Once all recording devices were started, the participant assembled the physical version of PEAT. For this assembly, it was important to make sure that the motion tracker Dtrack balls were placed on the frameless glasses, as displayed in Figure 26. Upon completion of the physical assembly, participants took the "Physical Assembly Survey" and answered a question regarding their ergonomic discomfort during the assembly process.

Figure 26: PEAT physical assembly example and point of view

Virtual Assembly

Again, continuing with the odd-numbered participants' process flow, before entering the virtual environment, participants were placed in the "Virtual Reality Training Environment" as displayed in Figure 27. This was to allow participants to familiarize themselves with the virtual environment, as well as learn the controls for part interaction. This environment contained a simple workbench (similar to what they would see in the PEAT virtual assembly environment) with 3 shapes. The shapes were programmed with the same snap-to-fit function allowing for part assembly. Additionally, the cylinder was threaded, and had the ability to be turned down into the table to provide participants an opportunity to trial a threaded component interaction. Participants were allowed to spend as much time in this environment as they wished up to 10 minutes. Figure 27: Virtual reality training environment

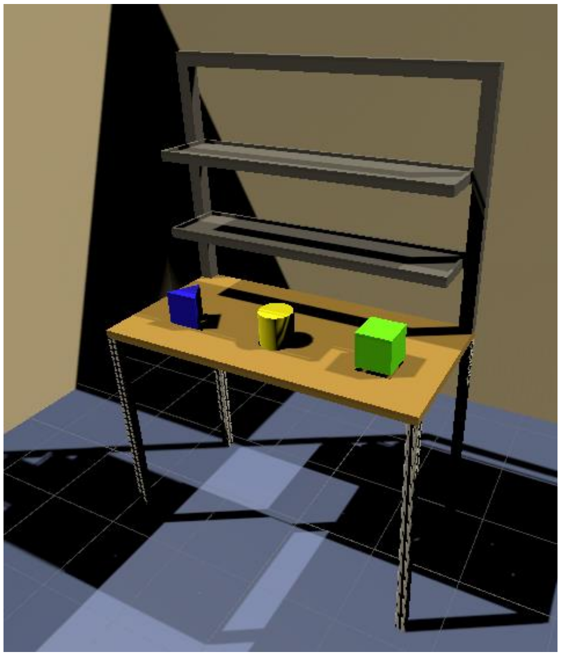


Figure 27: Virtual reality training environment

With all systems recording, the participants then assembled the virtual version of PEAT. The motion tracker balls were swapped to mount to the HMD as displayed in Figure 28. It is worth noting that some exaggerated movements were required for smaller part interactions with the controllers such as bolt torques. Following the virtual assembly, the participant took a "Virtual Assembly Survey" regarding both their ergonomic discomfort and their cybersickness.

Figure 28: PEAT virtual assembly example and point of view

Post-Study Survey

Finally, participants took a post study survey regarding their overall experience and were asked questions regarding the sufficiency of the training material, the accuracy of the virtual rendering, etc. (see Post-Study Survey for full details).

Data Analysis Plan

Equivalence Testing

Following an F test for equal variance, this study looked to utilize TOST equivalence testing [28]. Unlike standard hypothesis-testing statistics (such as t-test and ANOVA), in which studies with small p-values can claim that two sets of data are statistically significantly different, equivalence testing methods like TOST aim to prove that two groups of data are similar. In the present study, the research questions explored whether the two PEAT assembly conditions (virtual and physical) were similar.

Standard t-tests and ANOVAs result in one p-value, and if p is less than .05, it is reasonable to claim a significant difference. In a TOST test, both an upper and lower bound for the difference between the datasets are used [28]. Figure 29 provides a visual depiction of this concept. If the larger of the two p-values is below .05, statistically significant equivalence can be claimed. This approach makes the choice of upper and lower bounds a critical decision. There are many methods regarding how to reasonably select bounds, however all require sufficient justification [29]. The Minitab software application was used for TOST analysis [30]. Below are the justifications for the upper and lower bounds for each assessment system.

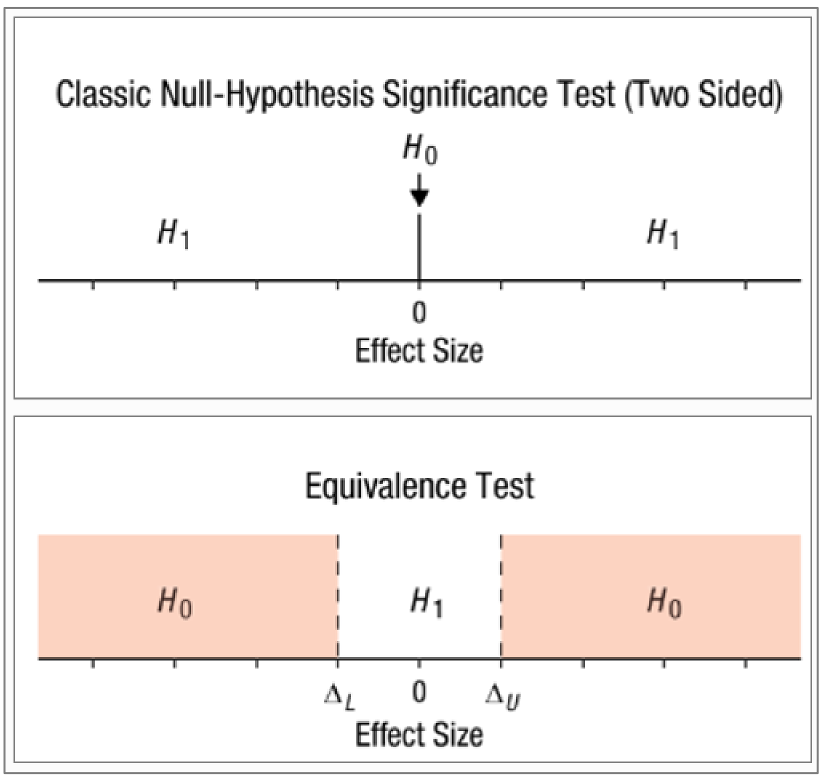


Figure 29: Classic Statistical Testing vs Equivalence Testing [28]

REBA/RULA Bounds

It is generally good practice to set your equivalence upper and lower bounds to be +/- 5-10% of the data's mean [29]. REBA and RULA presented a unique situation where this standard did not quite apply. As was shown in Figure 13 and Figure 15, the values for different risk ranges varied in size. There are multiple whole values which would classify processes as being the same risk level, e.g., on REBA, scores of 2-3 represent one risk level, while 8-10 represent another risk level. For this purpose, an alternative approach to deciding the bounds was taken. For both assessment tools, the average difference in scores to shift to a new risk level was 2. That said, the equivalence testing would be evaluating the difference in values between the physical and virtual REBA and RULA scores. For this reason, the lower equivalence limit was set at 0, indicating no difference in ergonomic risk values, while the upper equivalence limit was set at 2, since 2 is the average difference in scores to shift risk level. For the purposes of this study, this evaluation was not concerned with how far apart the risk scores were. If they fell within the same level of risk category from an ergonomic standpoint, they would be deemed the same.

HumanTech

Given the HumanTech Advanced Tool Priority Score risk ranges (see Figure 16), the upper and lower equivalence bounds were able to abide by the standard 5-10% rule. The overall mean of the HumanTech analysis data (both physical and virtual combined) produced an average of 20.05. 10% of this mean equates to 2, meaning similar to that of REBA/RULA, the lower equivalence limit was set at 0 and the upper equivalence limit was set at 2.

Delsys Bounds:

Due to the nature of EMG data, these voltages were presented in very small values. For this reason, abiding by 10% of the mean for the upper and lower equivalence limits was not quite relevant here. For example, some physical voltages hover around 1.0 (0.9, 0.9, 1.0, 1.1, etc.)

while the virtual data in some instances are around .02 (0.25, 0.2, 0.21, etc.). This would result in 10 of the physical data being around 0.1 and 10% of the virtual data around 0.02. the average of the entire data set (both physical and virtual) would be around .55 which makes it difficult to apply to either dataset. For this purpose, that a 90% confidence interval utilizing the differences in the two environments (physical and virtual) approach was utilized. To scale appropriately, the P value for this analysis was set at 1. In other words, if the confidence interval falls between 0 and 1 volts, it is considered equivalent.

Dtrack Bounds

The Dtrack positional data was normalized in the X, Y, and Z direction for all body tracking IDs (see Dtrack Equivalence Testing). This data was scaled to abide by a 0-100 range for equivalence analysis. For this reason, the 10% rule is applicable resulting in a lower equivalence limit of 0 and an upper equialvnce limit of 10.

Predictions

Given the known work from the literature review and the methods of the current study, the following predictions were made for each research question.

Research Question 1:

Is virtual reality a feasible substitute for physical ergonomic assessment? <u>RQ1 Prediction</u>: From a fluid data capture perspective (an analysis of the overall process) virtual reality will be a feasible substitute. From a stationary position standpoint, it is assumed there will be some caveats regarding what is feasible and what is not.

Research Question 2:

When comparing body tracking systems based on computer-vision, optical markers, and EMG sensors, which provides the closest results between the physical and virtual environments?

RQ2 Prediction: HumanTech is predicted to have the most repeatable metrics, as it is an all-encompassing representation of the assembly process. Dtrack will have the next closest metrics, for the rendering was built to scale within the room. Finally, Delsys will have the most variation in metrics, due to the part interaction circumstances induced by the virtual environment. Longer cycle times will lead to more required muscle activation for assembly and the variation in that data is expected to reflect this.

Research Question 3:

Will younger participants have a lower task cycle time in virtual reality than older participants? RQ3 Prediction: It is assumed that age will not have a large effect on virtual reality cycle time completion.

Research Question 4:

Will participants with prior VR experience perform movements in VR that more closely mirror movements in the physical world than those with less VR experience? RQ4 Prediction: Participants with prior virtual reality experience will have more repeatable metrics between the physical and virtual environment due to how comfortable they are immersed in the virtual environment.

Research Question 5:

Will participants with prior manufacturing experience perform movements in VR that more closely mirror movements in the physical world than those with less manufacturing experience? RQ5 Prediction: Manufacturing experience will not have a large impact on the repeatability of metrics between both environments.

Research Question 6:

Will participants who are more active have a lower REBA/RULA score? RQ6 Prediction: Participants who are more active on average will have a lower REBA/RULA score.

Research Question 7:

Will there be a difference between left-handed vs right-handed participants performance in the virtual environment? RQ7 Prediction: Due to the point of interaction in this virtual environment, it is assumed that those who are right-handed will have a higher cycle time than those who are left-handed.

Research Question 8:

Was the product easier to assemble in the physical or virtual environment based on self-reported survey results? RQ8 Prediction: Participants will self-report that the product was easier to assemble in the physical environment than the virtual environment.

Research Question 9:

Did participants' rating of comfort during assembly differ in the physical vs. virtual environment? RQ9 Prediction: Participants will self-report more discomfort in the virtual environment than the physical environment.

Research Question 10:

Did participant height have an impact on ergonomic risk score result? RQ10 Prediction: There will be a positive relationship between participants' height and ergonomic risk score (in other words, taller individuals will have a higher associated risk).

CHAPTER 4. RESULTS

The following results are presented according to the research questions, with Research Question 1 (Is virtual reality a feasible substitute for physical ergonomic assessment?) addressed last within the Discussion after considering all results.

Research Question 2

To address RQ2 (When comparing body tracking systems based on computer-vision, optical markers, and EMG sensors, which provides the closest results between the physical and virtual environments?), the results for physical and virtual assembly are compared below for each of the four tracking and movement analysis systems: REBA/RULA, HumanTech, Delsys, and Dtrack.

REBA/RULA

Inter-Rater Reliability Score

Because REBA/RULA scoring requires subjective human judgment, an inter-rater reliability score was calculated for the first 10 participants by two individuals who were responsible for performing the REBA and RULA analysis. Of 320 data points calculated by each individual, 232 points were in agreement, resulting in an inter-rater reliability score of 72.5%. This score was sufficiently high to allow the remaining 55 participants to have their REBA and RULA scores analyzed by one individual.

$$IRR = \frac{TA}{TR} * 100 = \frac{232}{320} * 100$$

$$IRR = 72.5\%$$

REBA Descriptive Statistics

Following the conclusion of all REBA assessments, each action’s score distributions were plotted. Table 10 displays the distributions for each of the eight stationary positions that were evaluated in via REBA assessment. These eight positions, a subset of the 14 assembly steps for PEAT, were selected in an attempt to capture a well-rounded analysis of the entire assembly process from start to finish. Assembly steps were selected from different points throughout the process. High, medium, and low range bin picks were selected in an attempt to capture the extremes of both cases, as well as a few of the major assembly steps/interactions with the part on the fixture.

Table 10: REBA assessment physical and virtual distributions

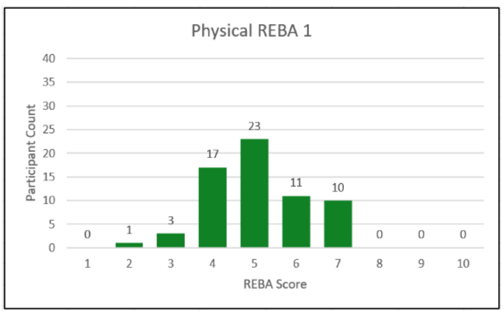
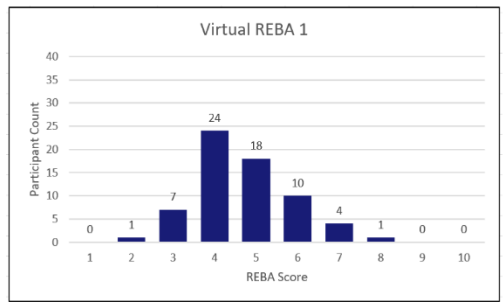
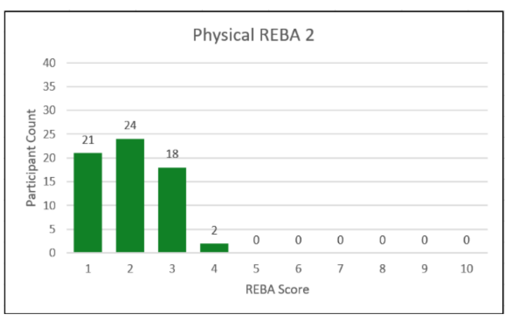
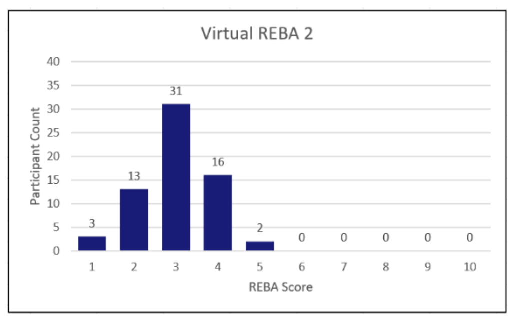
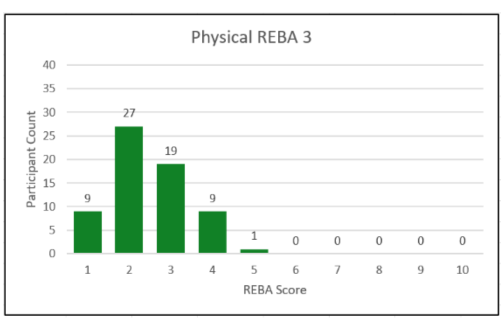
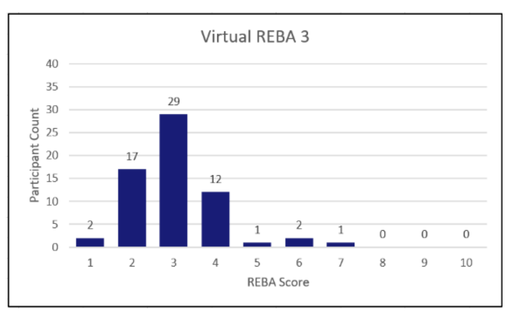
Position	Physical REBA	Virtual REBA
(1) Housing Pick		
(2) Housing Install		
(3) Slider Block Install		

Table 10 Continued

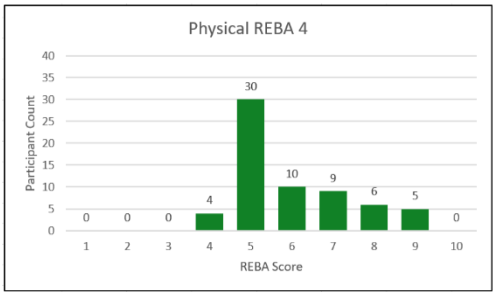
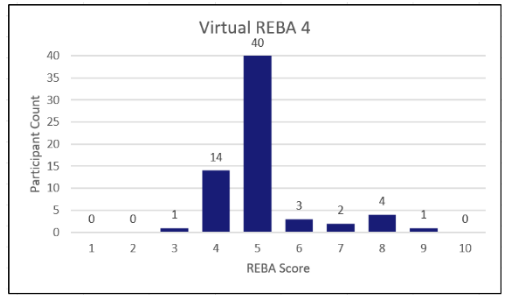
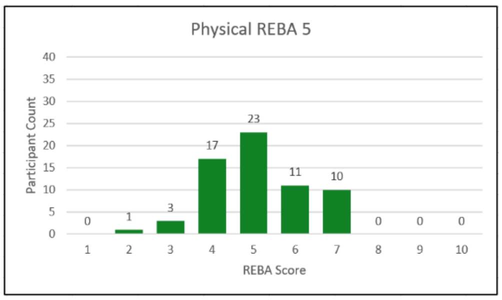
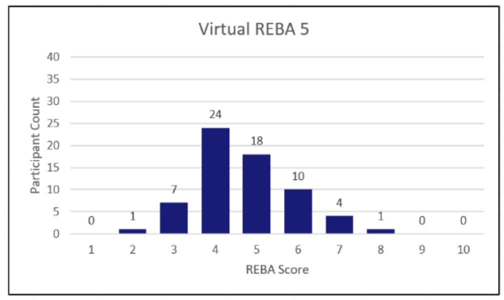
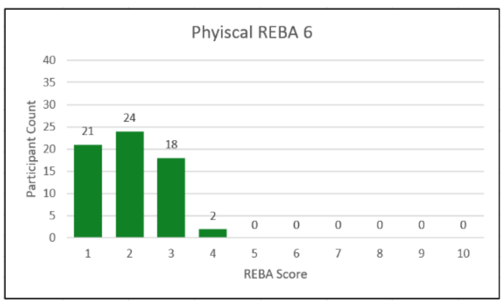
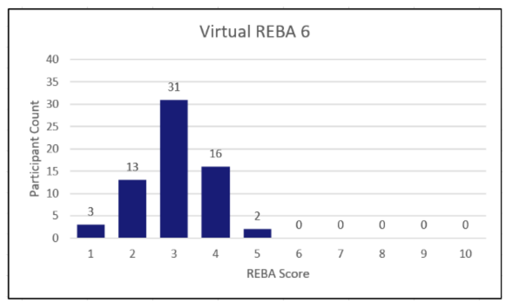
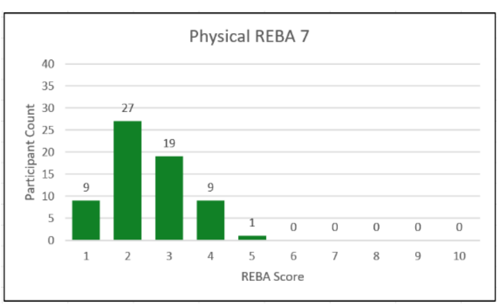
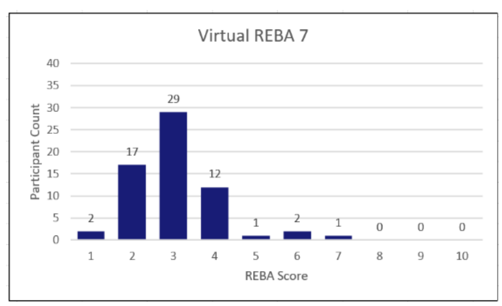
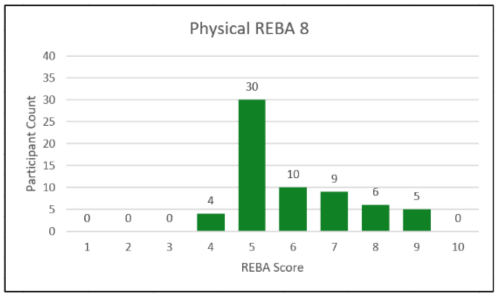
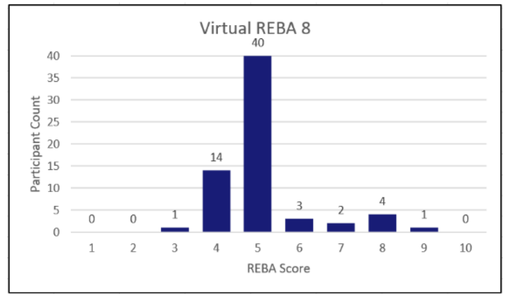
<table>
<tr>
<td>(4) Top Left Bin Pick</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(5) Fixture Rotation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(6) Bottom Right Bin Pick</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(7) Center Middle Bin Pick</td>
<td></td>
<td></td>
</tr>
</table>

Table 10 Continued

(8) Threaded Shaft Install		

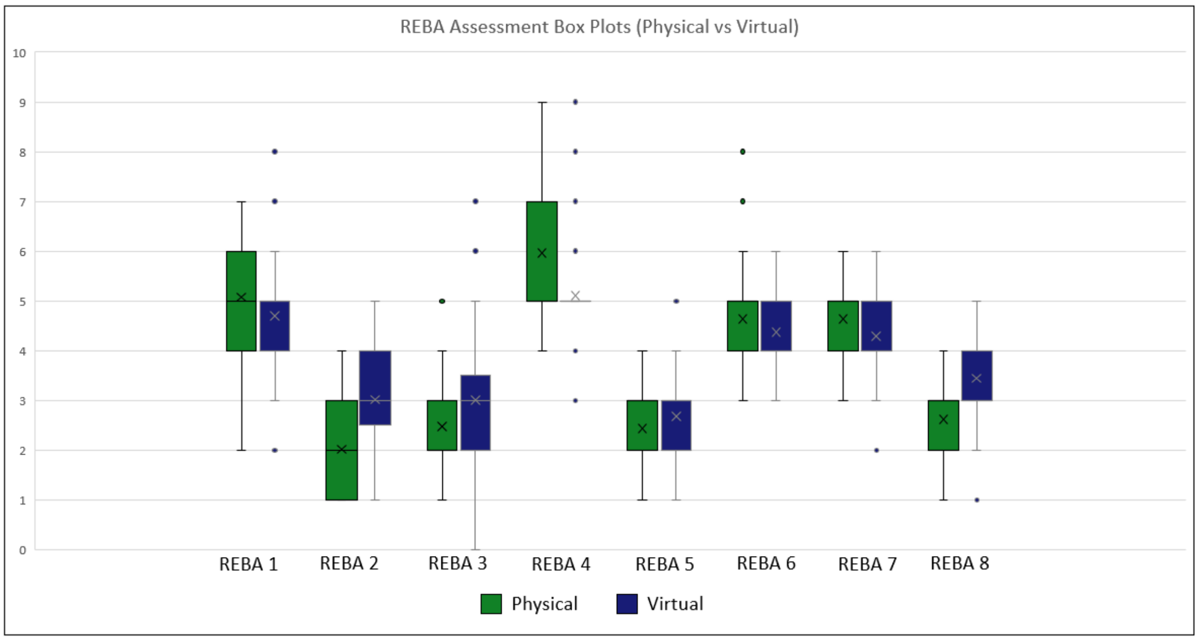


Figure 30: REBA assessment box plots (physical vs virtual) for each of the 8 assembly positions

Summary statistics for each of the REBA assessments in both physical and virtual environments are displayed below in Table 11. The average mean for physical REBA assessments was 3.73 while the average mean for the virtual REBA assessments was 3.83.

Table 11: REBA summary statistics by position- physical and virtual

REBA Assessment Position	Mean		Std. Dev.		Min		Max	
	P	V	P	V	P	V	P	V
(1) Housing Pick	5.07	4.69	1.18	1.18	2	2	7	8
(2) Housing Install	2.01	3.02	0.86	0.87	1	1	4	5
(3) Slider Block Install	2.43	3.05	0.91	1.09	1	1	4	7
(4) Top Left Bin Pick	6.00	5.11	1.39	1.12	4	3	9	9
(5) Fixture Rotation	2.44	2.68	0.85	0.83	1	1	4	5
(6) Bottom Right Bin Pick	4.63	4.37	1.31	0.86	3	3	8	6
(7) Center Middle Bin Pick	4.63	4.29	0.68	0.86	3	2	6	6
(8) Threaded Shaft Install	2.61	3.45	0.89	0.83	1	1	4	5

RULA Descriptive Statistics

Similar to that of the REBA distributions, the RULA distributions were plotted in the same manner. Table 12 displays the distributions for each of the eight stationary positions that were evaluated in via RULA assessment. Again, these eight positions were selected in an attempt to capture a well-rounded analysis of the entire assembly process from start to finish.

Table 12: RULA assessment physical and virtual distributions

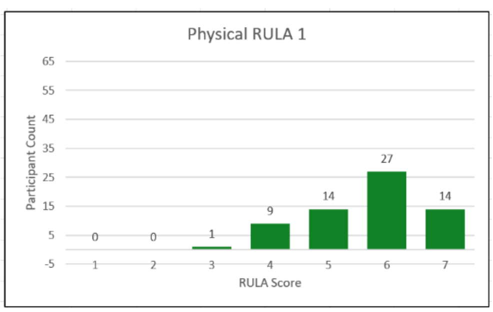
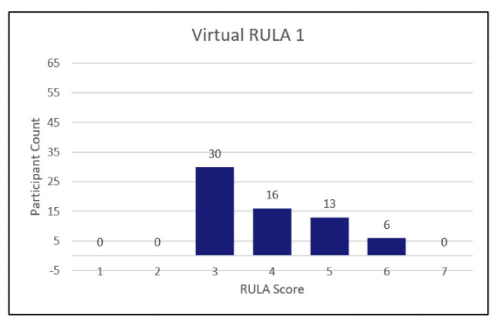
Position	Physical RULA	Virtual RULA
(1) Housing Pick		

Table 12 Continued

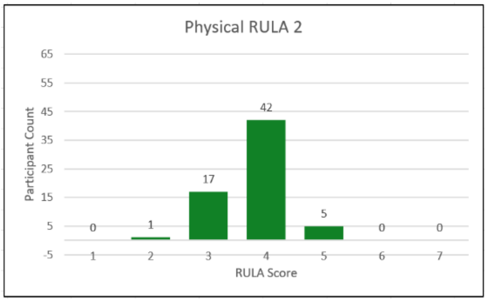
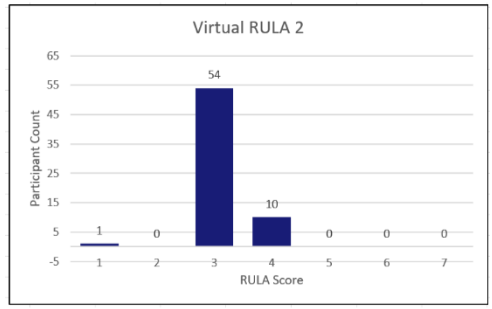
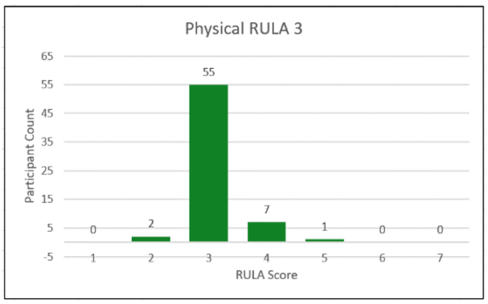
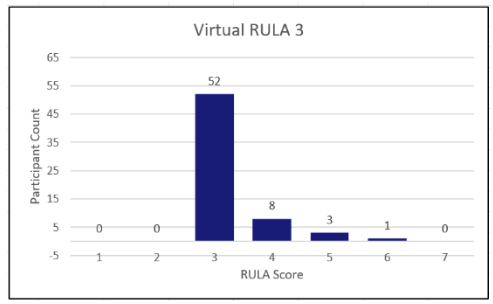
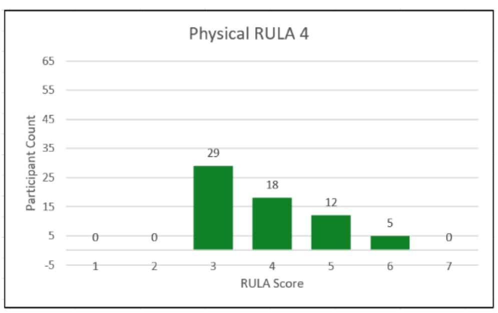
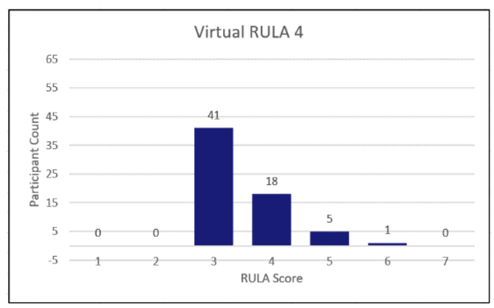
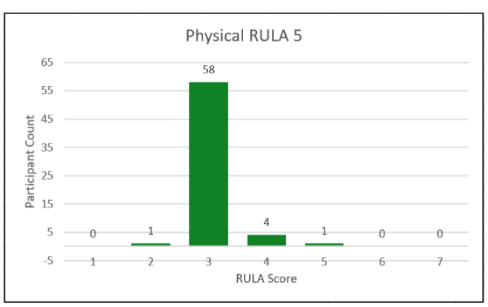
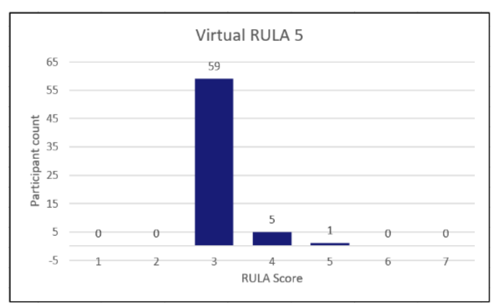
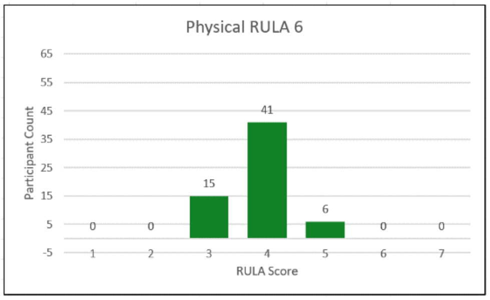
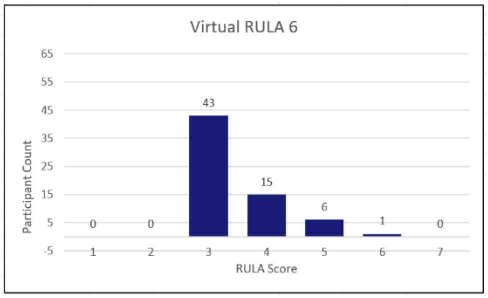
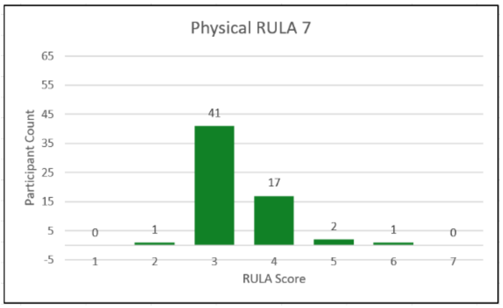
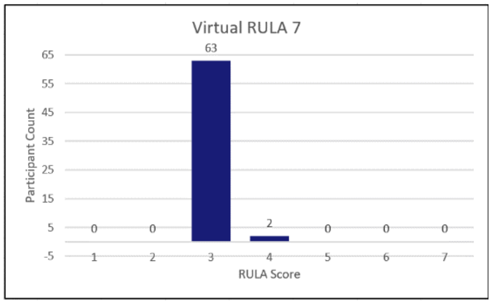
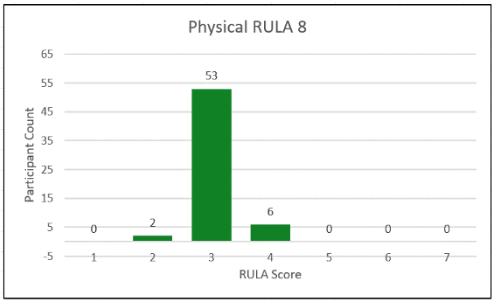
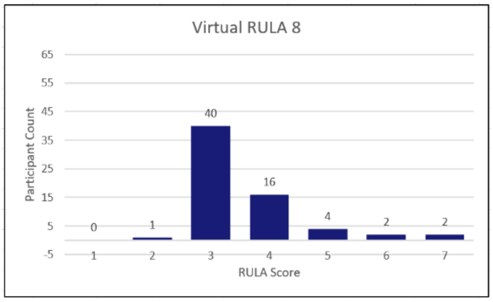
(2) Housing Install		
(3) Slider Block Install		
(4) Top Left Bin Pick		
(5) Fixture Rotation		

Table 12 Continued

(6) Bottom Right Bin Pick		
(7) Center Middle Bin Pick		
(8) Threaded Shaft Install		

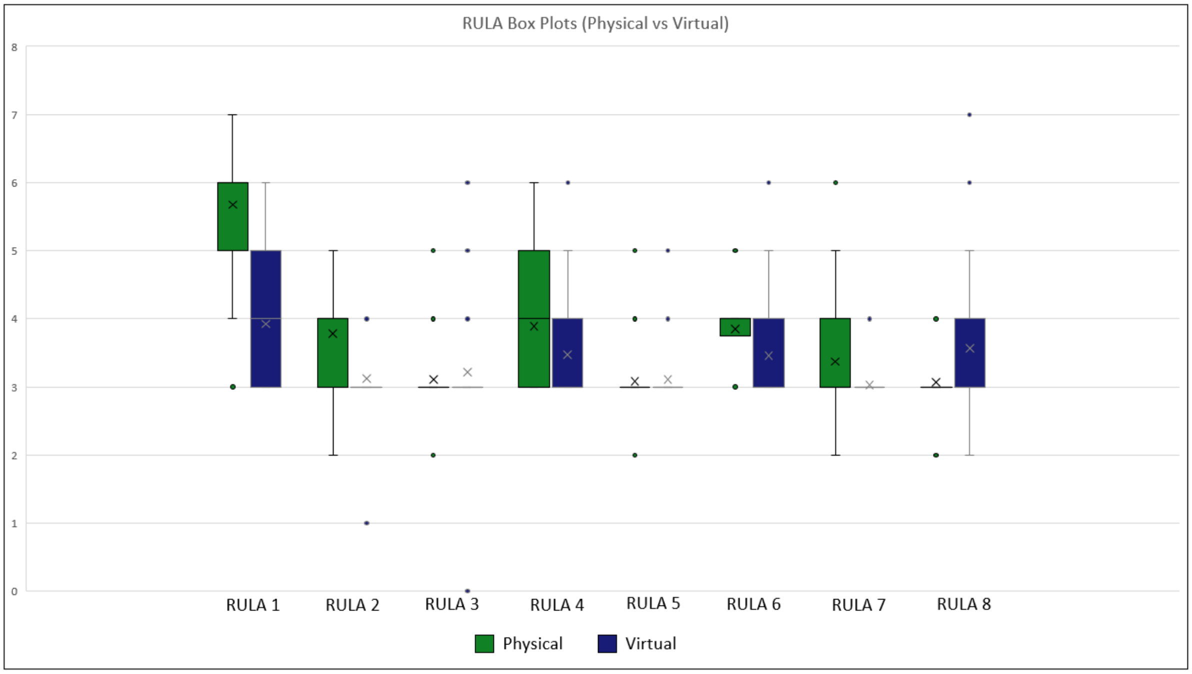


Figure 31: RULA assessment box plots (physical vs virtual) for each of the 8 assembly positions

Summary statistics for each of the RULA assessments in both physical and virtual environments are displayed below in Table 13. The average mean for physical RULA assessments was 3.73 while the average mean for the virtual RULA assessments was 3.37.

Table 13: RULA summary statistics by position- physical and virtual

RULA Assessment Position	Mean		Std. Dev.		Min		Max	
	P	V	P	V	P	V	P	V
(1) Housing Pick	5.68	3.92	1.02	1.02	3	3	7	6
(2) Housing Install	3.78	3.12	0.6	0.45	2	1	5	4
(3) Slider Block Install	3.11	3.27	0.44	0.62	2	3	5	6
(4) Top Left Bin Pick	3.9	3.48	0.98	0.71	3	3	6	6
(5) Fixture Rotation	3.08	3.11	0.37	0.36	2	3	5	5
(6) Bottom Right Bin Pick	3.85	3.46	0.57	0.73	3	3	5	6
(7) Center Middle Bin Pick	3.37	3.03	0.66	0.17	2	3	6	4
(8) Threaded Shaft Install	3.07	3.57	0.36	0.98	2	2	4	7

REBA/RULA Equivalence Testing

Table 14 displays the results from the equivalence testing from both the REBA and RULA assessment results. This analysis concluded that 3 out of 8 postures in REBA were equivalent, and 4 out of 8 postures in RULA were equivalent. Both assessments indicated the top left bin pick and the middle bin pick were equivalent in both environments. Both assessments also indicated that the threaded shaft install, the slider block install, and the fixture rotation were not equivalent. Overall, REBA and RULA found that some postures were deemed equivalent and some were not, suggesting that VR analysis was sufficient for some postures and not others.

Table 14: REBA & RULA equivalence test results after comparing physical and virtual conditions for each posture

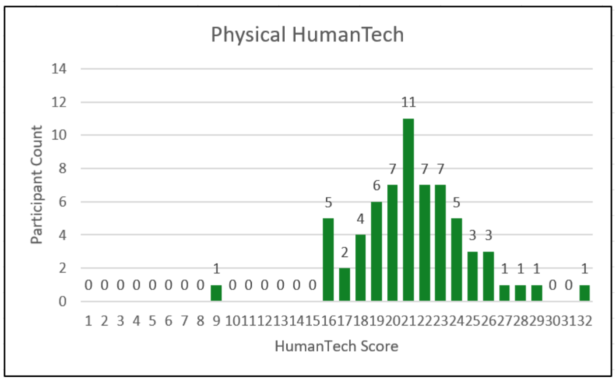
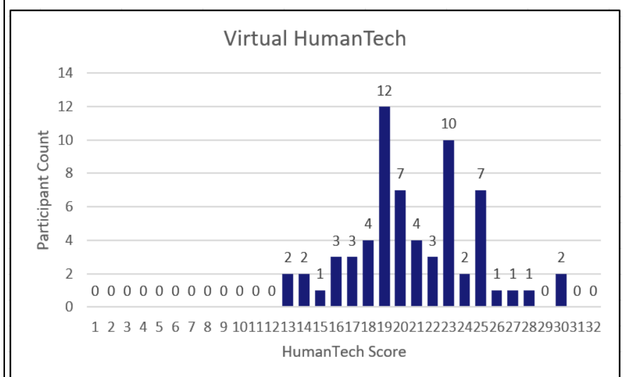
Posture	REBA Equivalent? (larger p-value)	RULA Equivalent? (larger p-value)
Housing Pick	Yes (.008)	No (.074)
Housing Install	No (1.000)	Yes (< .001)
Slider Block Install	No (1.000)	No (.993)
Top Left Bin Pick	Yes (< .001)	Yes (< .001)
Fixture Rotation	No (.969)	No (.679)
Bottom Right Bin Pick	No (.060)	Yes (< .001)
Center Middle Bin Pick	Yes (.006)	Yes (< .001)
Threaded Shaft Install	No (1.000)	No (1.000)

HumanTech

HumanTech Descriptive Statistics:

HumanTech analyses were performed for both physical and virtual participants. Table 15 displays the distributions for both the physical and virtual HumanTech assessments. The physical environment yielded an average risk score of 20.3 (SD 3.6, min 8, max 31) across all participants. This places the average physical ergonomic risk in the lowest value in the moderate risk category according to the HumanTech scale. The virtual environment had an average risk score of 19.8 (SD 3.8, min 12, max 29). These results can be compared in Table 16. This places the average virtual ergonomic risk score in the highest value of the low risk category. Therefore, on average, the physical environment had an additional 0.5 points of risk consideration compared with the virtual environment.

Table 15: HumanTech physical vs virtual distributions across participants

<table>
<tr><th>Physical HumanTech Distribution</th><th>Virtual HumanTech Distribution</th></tr>
<tr><td>
</td><td>
</td></tr>
</table>

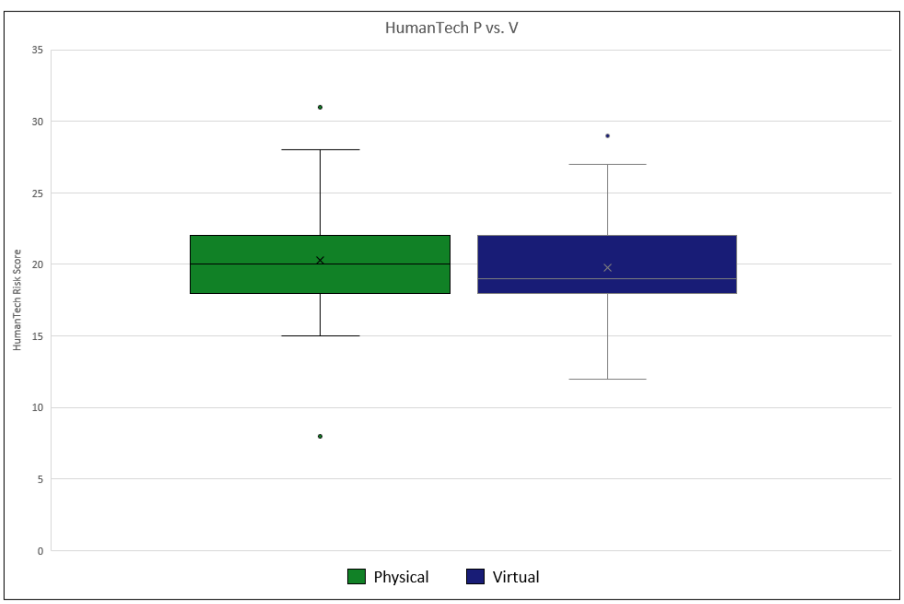


Figure 32: HumanTech assessment box plots (physical vs virtual)

Table 16: HumanTech assessment summary statistics- physical vs virtual

HumanTech	Mean		Std. Dev.		Min		Max	
	P	V	P	V	P	V	P	V
HumanTech Assessment	20.3	19.8	3.6	3.8	8	12	31	29

HumanTech Equivalence Testing

Tables below and Figure 33 display the results of the HumanTech Equivalence Testing. It is important to note that unlike the REBA/RULA assessments, HumanTech is a fluid and continuous analysis over the full duration of the assembly process. The assessment looks at the process as a whole (across an entire video recording), providing an all-encompassing assessment as opposed to a single instant in time. This assessment considers duration of each posture as well. As displayed in Table 20, from a HumanTech standpoint, equivalence between the physical and virtual assembly can be claimed based on the significant p-values at both upper and lower bounds.

Table 17: HumanTech Mintab equivalence testing method result

Method	
Test Mean =	Mean of Physical
Reference Mean =	Mean of Virtual

Table 18: HumanTech Mintab equivalence testing descriptive statistics results

Descriptive Statistics				
Variable	**N**	**Mean**	**StDev**	**SE Mean**
Physical	120	20.44	3.64	0.33
Virtual	120	19.72	3.74	0.34

Table 19: HumanTech Mintab equivalence testing difference (mean physical - mean virtual) result and equivalence declaration.

Difference: Mean (Physical)-Mean (Virtual)				
Difference	**StDev**	**SE**	**95%CI for Equivalence**	**Equivalence Interval**
0.71	4.63	0.4	(0.015, 1.41)	(0,2)
CI is within the equivalence interval. Can claim equivalence.				

Table 20: HumanTech Minitab equivalence testing test result

Test			
Null Hypothesis:	Difference <= 0 or Difference >= 2		
Alternative Hypothesis:	0 < Difference < 2		
α level:	0.05		
Null Hypothesis	**DF**	**T-Value**	**P-Value**
Difference <=0	119	1.69	.046
Difference >=2	119	-3.03	.001
The greater p-value is .046, which is < .05. Can claim equivalence.			

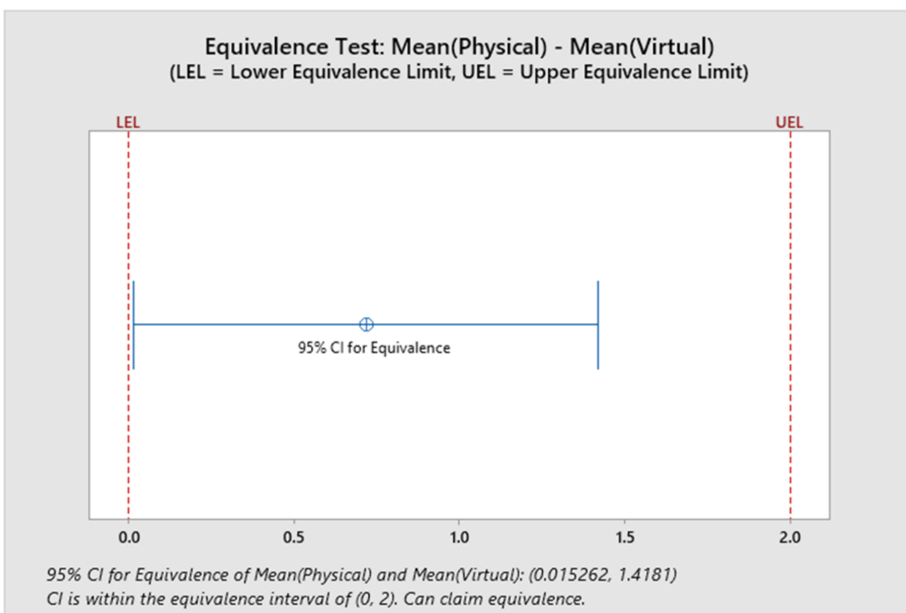


Figure 33: HumanTech equivalence testing upper and lower equivalence limits visual depiction (graphic from Minitab output)

Delsys

Delsys Descriptive Statistics

The Delsys system collected muscle stimulation fluidly over the full duration of the assembly process for 10 different muscle locations on the upper body of each participant. This system takes muscle stimulation and equates it to a voltage. This data imported as negative EMG values and was converted from a frequency-based dataset to a time-based data set via a MATLAB program, providing positive accurate voltages. Following the full data collection, a cycle time analysis was performed for each assembly task. These cycle times were utilized to separate the data into each individual action, allowing the data for each assembly step to be summed and compared. The figures below compare the cumulative average muscle stimulation in voltage across all participants for each of the 10 sensors for each of 14 assembly actions in both the physical and virtual environment.

As stated above, the virtual environment required exaggerated movements for smaller component interactions and threaded components such as the swivel knob, cover bolts, and lifting bracket bolts. From a stationary ergonomic assessment standpoint, this was not a large concern, as during the assembly steps themselves, the body is in a relatively neutral position. When evaluating an instant in time it is not very concerning, but from the standpoint of a fluid capture standpoint such as Delsys, the repetition of each movement is weighted heavily and has an impact on the overall analysis. As the figures below display, the virtual environment resulted in significantly higher muscle stimulation than that of the physical environment.

It is also important to note that these sensors should not be compared across one another (e.g. comparing S1 results with S2 results), since different muscles of the human body have different maximum contractions. For the purposes of this research however, this data is still relevant without normalization of the data, for this study is only looking at the difference between the physical and virtual conditions of each individual muscle, not the sensors across one another.

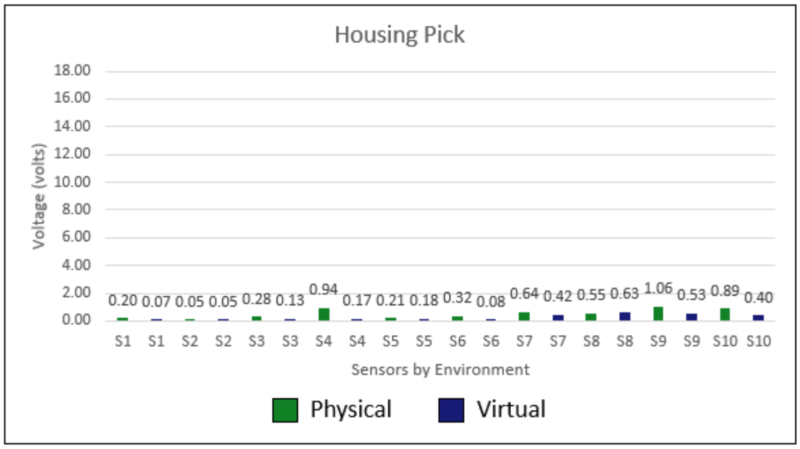


Figure 34: Delsys housing pick chart displaying the average cumulative muscle stimulation across all participants in both the physical and virtual environment.

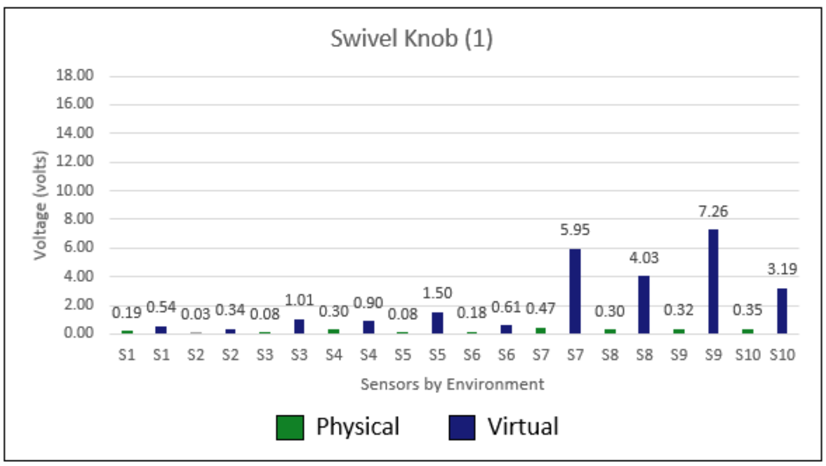


Figure 35: Delsys swivel knob (1) chart displaying the average cumulative muscle stimulation across all participants in both the physical and virtual environment.

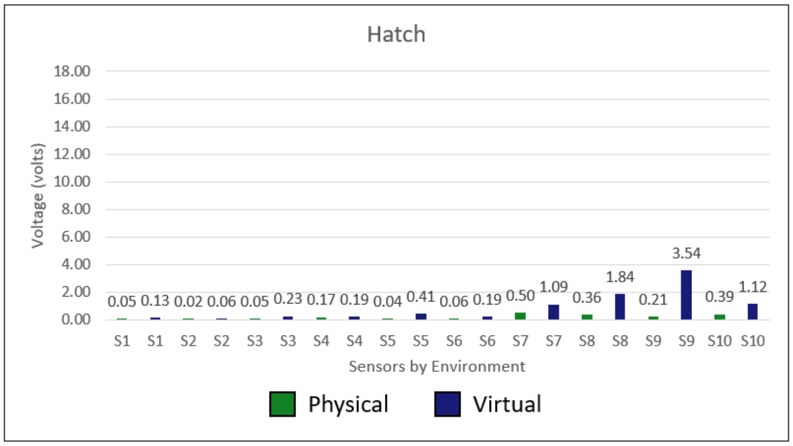


Figure 36: Delsys hatch chart displaying the average cumulative muscle stimulation across all participants in both the physical and virtual environment.

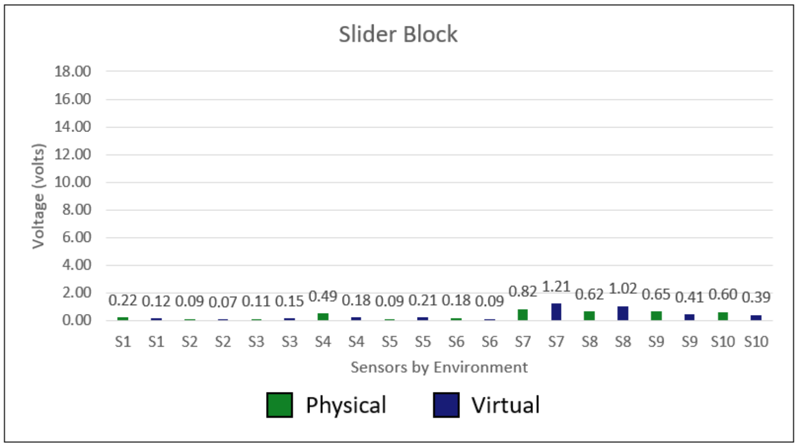


Figure 37: Delsys slider block chart displaying the average cumulative muscle stimulation across all participants in both the physical and virtual environment.

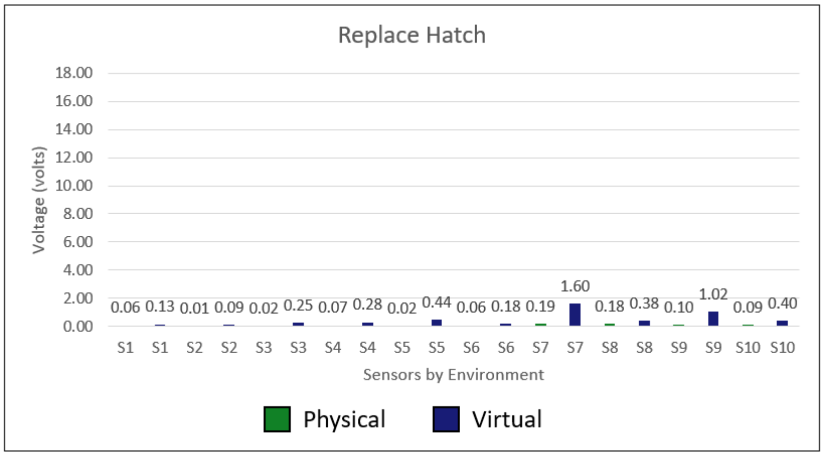


Figure 38: Delsys replace hatch chart displaying the average cumulative muscle stimulation across all participants in both the physical and virtual environment.

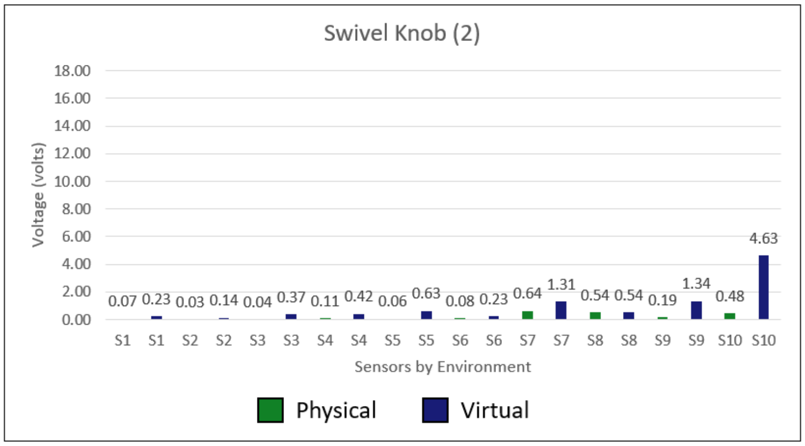


Figure 39: Delsys swivel knob (2) chart displaying the average cumulative muscle stimulation across all participants in both the physical and virtual environment.

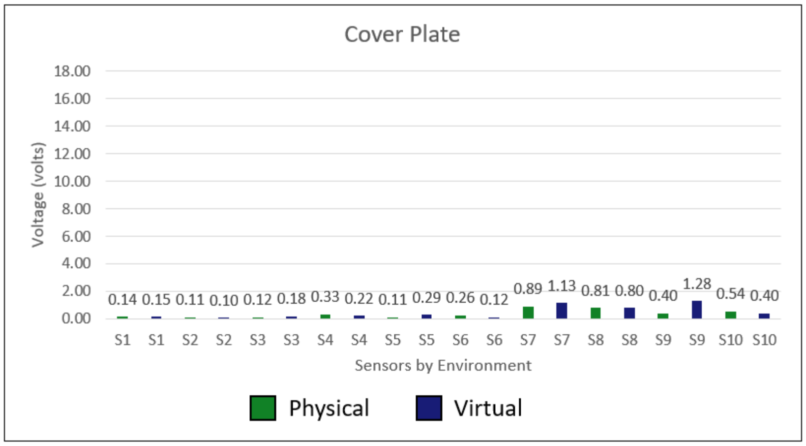


Figure 40: Delsys cover plate chart displaying the average cumulative muscle stimulation across all participants in both the physical and virtual environment.

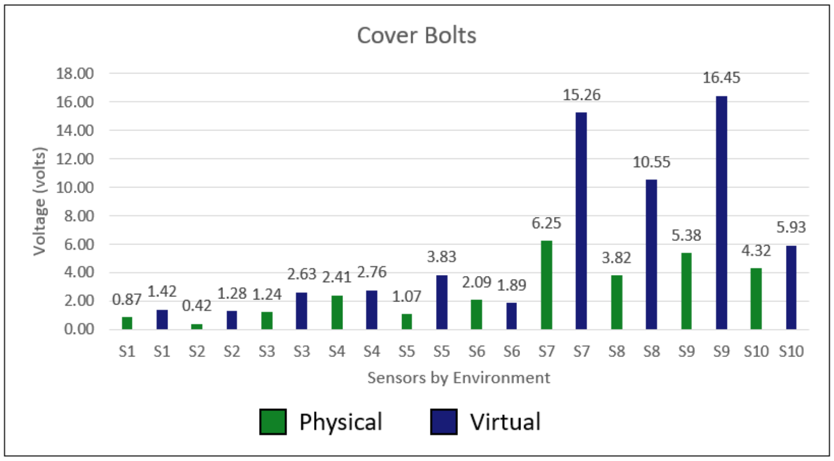


Figure 41: Delsys cover bolts chart displaying the average cumulative muscle stimulation across all participants in both the physical and virtual environment.

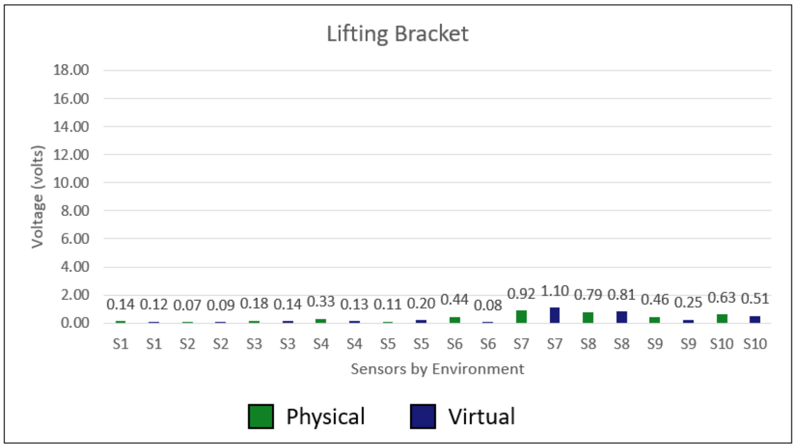


Figure 42: Delsys lifting bracket chart displaying the average cumulative muscle stimulation across all participants in both the physical and virtual environment.

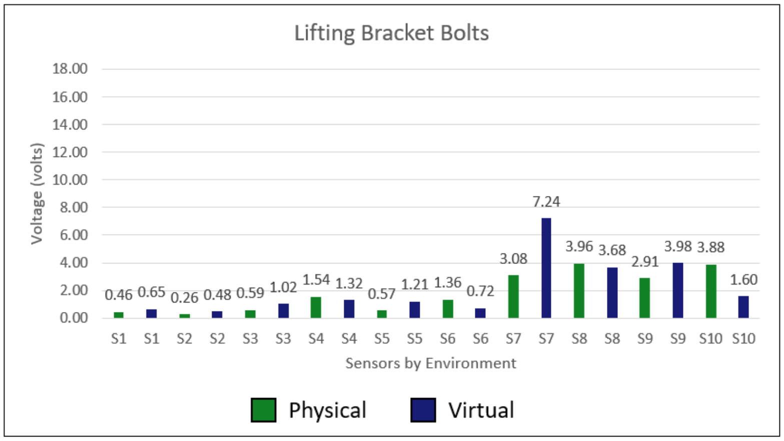


Figure 43: Delsys lifting bracket bolts chart displaying the average cumulative muscle stimulation across all participants in both the physical and virtual environment.

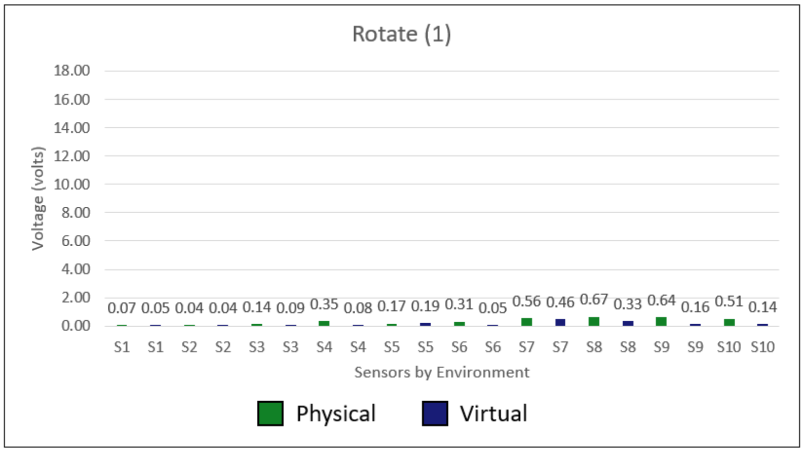


Figure 44: Delsys rotate (1) chart displaying the average cumulative muscle stimulation across all participants in both the physical and virtual environment.

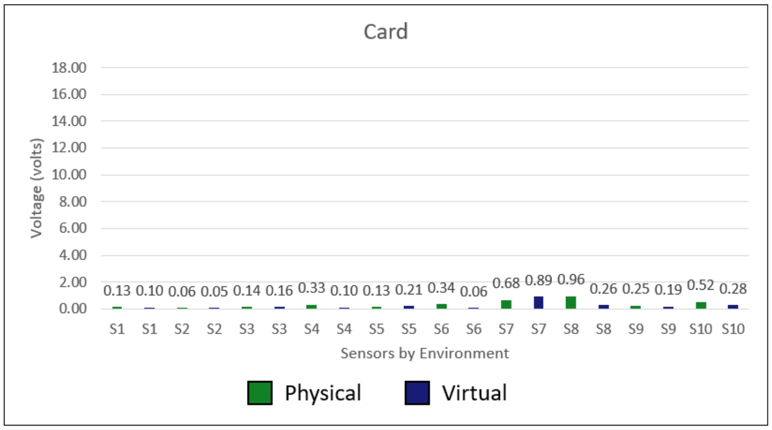


Figure 45: Delsys card chart displaying the average cumulative muscle stimulation across all participants in both the physical and virtual environment.

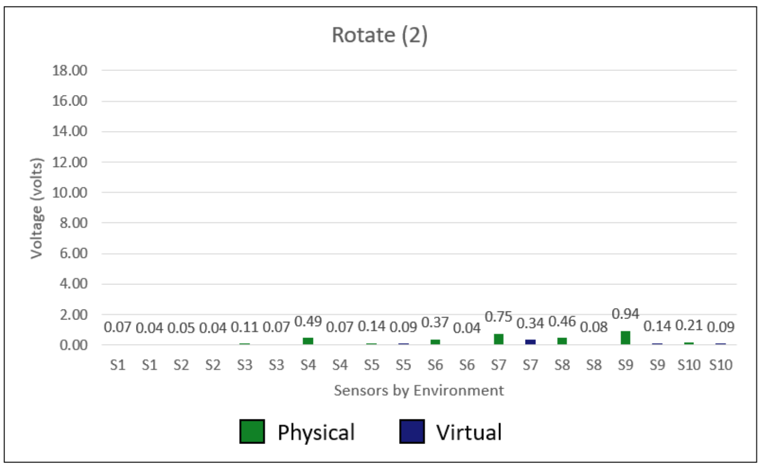


Figure 46: Delsys rotate (2) chart displaying the average cumulative muscle stimulation across all participants in both the physical and virtual environment.

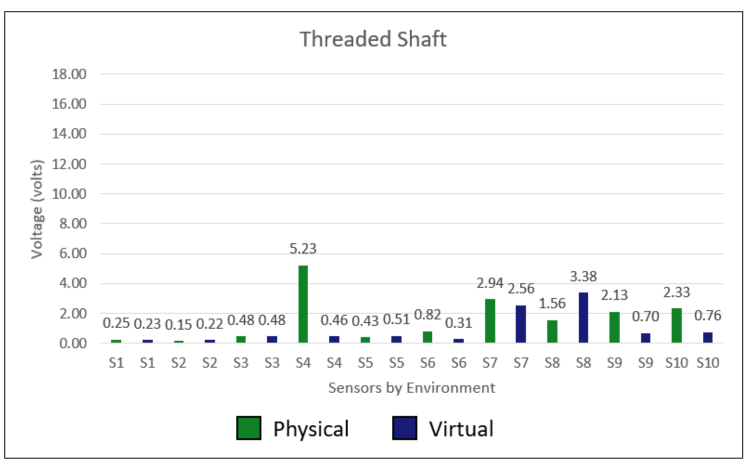


Figure 47: Delsys threaded shaft chart displaying the average cumulative muscle stimulation across all participants in both the physical and virtual environment.

Following individual task analysis, the cumulate muscle stimulation across all participants for each sensor were evaluated. Table 21 and Figure 48 display the cumulative muscle stimulation across all participants by sensor. It is clear that sensors 7 (R extensor digitorum- right lower outer arm), 8 (L extensor digitorum- left lower outer arm), 9 (R trapezius upper fibers- right back of neck) and 10 (L trapezius upper fibers- left back of neck) experienced the most muscle activation in both environments. Sensor 7 and 8's high voltage can be explained by the fact that this assembly required light weight part assembly with fairly meticulous movements requiring dexterity of the hands (such as small bolt torques), therefore engaging the outer arm muscles. Sensors 9 and 10 values, while not particularly anticipated, do provide a unique data point in the aspect that both environments required quite a bit of head movement. This is likely due to participants' unfamiliarity with the assembly process and environment.

Table 21: Delsys values for cumulative muscle stimulation across all participants in both the physical and virtual environments

Sensor	Physical	Virtual
S1	176.46	231.28
S2	83.32	177.12
S3	215.22	401.01
S4	778.49	423.32
S5	194.77	575.12
S6	413.70	269.72
S7	1163.60	2365.44
S8	940.59	1656.14
S9	942.45	2168.18
S10	949.56	1126.58

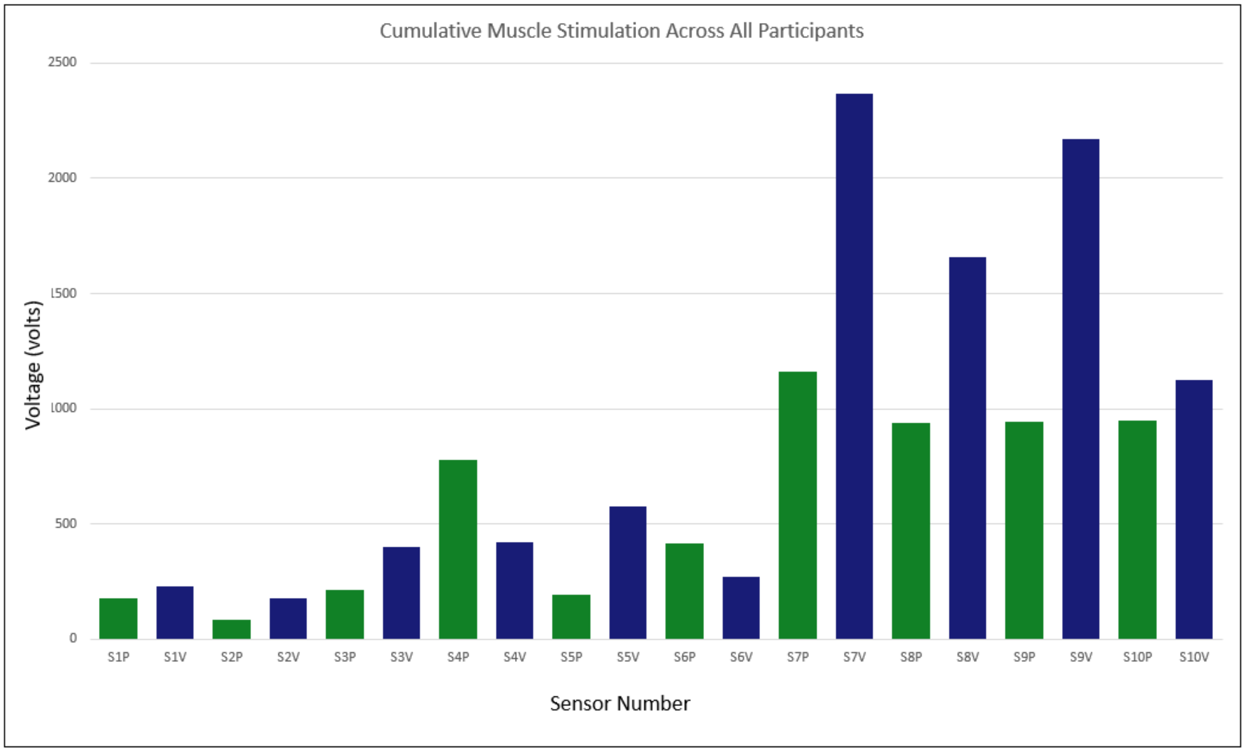


Figure 48: Delsys cumulative muscle stimulation across all participants in both the physical and virtual environments

Delsys Equivalence Testing

Cumulative Sensor Analysis

As stated previously, the 90% confidence interval of the differences between the two environments was calculated to determine equivalence. Table 22 displays the results of the confidence interval calculated for each sensor. Additionally, Table 23 displays a “yes” or “no” style table (green indicating equivalence in both environments, red indicating no equivalence) in both environments based on muscle stimulation. Of the 10 sensor placements, one out of the 10 total sensor locations indicated equivalence. The conclusion we can draw from this is that for the right shoulder held the only sensor that was able to be deemed equivalent from a muscle stimulation standpoint.

Table 22: 90% CI results from the difference in muscle stimulation across all participants and all assembly activities for each sensor. Green indicates equivalence; red indicates non-equivalence.

Variable	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
Average	0.23	0.16	0.38	1.04	0.56	0.55	2.80	2.48	3.18	2.00
StDev	0.61	0.44	0.91	9.26	1.38	2.51	18.08	13.65	26.18	12.36
Margin of Error	0.03	0.03	0.05	0.52	0.08	0.14	1.02	0.77	1.48	0.70
Lower Limit	0.20	0.14	0.33	0.52	0.48	0.41	1.78	1.71	1.69	1.30
Upper Limit	0.27	0.19	0.43	1.57	0.64	0.69	3.83	3.25	4.66	2.70
90% CI	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90
N	843	843	843	843	843	843	843	843	843	843
Equvalence Limits										
Average	0.23	0.16	0.38	1.04	0.56	0.55	2.80	2.48	3.18	2.00
10%	0.02	0.02	0.04	0.10	0.06	0.06	0.28	0.25	0.32	0.20
LEL	0.21	0.15	0.34	0.94	0.50	0.50	2.52	2.23	2.86	1.80
UEL	0.26	0.18	0.42	1.15	0.62	0.61	3.08	2.73	3.50	2.20

Table 23: Equivalence declaration by sensor and body location

Sensor	Equivalent Result	Muscle Name	Description
S1	Yes	R Deltoid	Right Shoulder
S2	No	L Deltoid	Left Shoulder
S3	No	R Biceps Brachi	Right Upper Inner Arm
S4	No	L Biceps Prachi	Left Upper Inner Arm
S5	No	R Flexor Carpi Radialis	Right Lower Inner Arm
S6	No	L Flexor Carpi Radialis	Left Lower Inner Arm
S7	No	R Extensor Digitorum	Right Lower Outer Arm
S8	No	L Extensor Digitorum	Left Lower Outer Arm
S9	No	R Trapezius Upper Fibers	Right Back of Neck
S10	No	L Trapezius Upper Fibers	Left Back of Neck

Sensor by Position Analysis

Taking the analysis one step further, the cumulative muscle stimulation for the duration of each assembly step was recorded. The same 90% confidence interval of the differences between the two environments was calculated to determine equivalence for each assembly step and each sensor. Table 27 through Table 40 through display the 90% confidence interval for equivalence testing broken down by each assembly task (indicated by Table 26) as well as by each sensor (placement indicated by Table 25). Table 24 provides an equivalence summary of Table 27 through Table 40 at a single glance. Unfortunately breaking down the evaluation this far only provided one out of 140 evaluation points. This again is likely due to the short comings of utilizing the VRTK package for part interaction. The handle grip buttons were used in an attempt to simulate part grabbing, however even with this consideration the data unfortunately did not match up. A majority of the upper and lower equivalence limits (+/-10% of the mean of each task), had a higher range than that of the confidence interval. For the environment and circumstances in this study, it is reasonable to argue that EMG analysis is not a valid ergonomic assessment in a virtual digital twin scenario.

Table 24: Delsys equivalence testing results summary by sensor and task

Delsys Equivalence Results (by sensor by task)														
Sensor	Task 1	Task 2	Task 3	Task 4	Task 5	Task 6	Task 7	Task 8	Task 9	Task 10	Task 11	Task 12	Task 13	Task 14
1	No	No	No	No	No	No	No	No	No	No	No	No	No	No
2	Yes	No	No	No	No	No	No	No	No	No	No	No	No	No
3	No	No	No	No	No	No	No	No	No	No	No	No	No	No
4	No	No	No	No	No	No	No	No	No	No	No	No	No	No
5	No	No	No	No	No	No	No	No	No	No	No	No	No	No
6	No	No	No	No	No	No	No	No	No	No	No	No	No	No
7	No	No	No	No	No	No	No	No	No	No	No	No	No	No
8	No	No	No	No	No	No	No	No	No	No	No	No	No	No

Table 24 Continued

Sensor	Task 1	Task 2	Task 3	Task 4	Task 5	Task 6	Task 7	Task 8	Task 9	Task 10	Task 11	Task 12	Task 13	Task 14
9	No	No	No	No	No	No	No	No	No	No	No	No	No	No
10	No	No	No	No	No	No	No	No	No	No	No	No	No	No

Table 25: Delsys sensor location key

Sensor	Muscle Name	Description
S1	R Deltoid	Right Shoulder
S2	L Deltoid	Left Shoulder
S3	R Biceps Brachi	Right Upper Inner Arm
S4	L Biceps Prachi	Left Upper Inner Arm
S5	R Flexor Carpi Radialis	Right Lower Inner Arm
S6	L Flexor Carpi Radialis	Left Lower Inner Arm
S7	R Extensor Digitorum	Right Lower Outer Arm
S8	L Extensor Digitorum	Left Lower Outer Arm
S9	R Trapezius Upper Fibers	Right Back of Neck
S10	L Trapezius Upper Fibers	Left Back of Neck

Table 26: Delsys task analysis key

Task	Description
Task 1	Housing Pick
Task 2	Swivel Knob (1)
Task 3	Hatch
Task 4	Slider Block
Task 5	Replace Hatch
Task 6	Swivel Knob (2)
Task 7	Cover Plate
Task 8	Cover Bolts
Task 9	Lifting Bracket
Task 10	Lifting Bracket Bolts
Task 11	Rotate (1)
Task 12	Card
Task 13	Rotate (2)
Task 14	Threaded shaft

Table 27: 90% CI results from the difference in muscle stimulation across all participants by sensor for Task 1. Green indicates equivalence; red indicates non-equivalence.

Task 1: Housing Pick										
Sensor	1	2	3	4	5	6	7	8	9	10
Average	0.15	0.03	0.19	0.81	0.16	0.26	0.59	0.64	0.68	0.54
StDev	0.90	0.03	0.15	4.61	0.17	0.66	2.01	2.69	2.00	2.27
Margin of Error	0.19	0.01	0.03	0.97	0.04	0.14	0.42	0.57	0.42	0.48
Lower Limit	-0.04	0.02	0.16	-0.16	0.12	0.12	0.16	0.07	0.26	0.06
Upper Limit	0.34	0.03	0.22	1.78	0.20	0.40	1.01	1.21	1.10	1.02
90% CI	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90
N	61	61	61	61	61	61	61	61	61	61
Equivalence Limits										
Average	0.15	0.03	0.19	0.81	0.16	0.26	0.59	0.64	0.68	0.54
10%	0.02	0.00	0.02	0.08	0.02	0.03	0.06	0.06	0.07	0.05
LEL	0.14	0.02	0.17	0.73	0.14	0.23	0.53	0.58	0.61	0.49
UEL	0.17	0.03	0.21	0.89	0.18	0.28	0.65	0.70	0.74	0.60

Table 28: 90% CI results from the difference in muscle stimulation across all participants by sensor for Task 2. Green indicates equivalence; red indicates non-equivalence.

Task 2: Swivel Knob (1)										
Sensor	1	2	3	4	5	6	7	8	9	10
Average	0.60	0.31	0.91	0.98	1.38	0.63	5.54	3.99	7.10	3.21
StDev	1.24	0.39	1.39	1.67	1.90	0.99	25.51	21.10	36.39	11.61
Margin of Error	0.26	0.08	0.29	0.35	0.40	0.21	5.37	4.44	7.66	2.44
Lower Limit	0.34	0.23	0.62	0.63	0.98	0.42	0.17	-0.45	-0.57	0.77
Upper Limit	0.86	0.39	1.20	1.33	1.78	0.84	10.91	8.44	14.76	5.66
90% CI	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90
N	61	61	61	61	61	61	61	61	61	61
Equivalence Limits										
Average	0.60	0.31	0.91	0.98	1.38	0.63	5.54	3.99	7.10	3.21
10%	0.06	0.03	0.09	0.10	0.14	0.06	0.55	0.40	0.71	0.32
LEL	0.54	0.28	0.82	0.88	1.24	0.57	4.98	3.59	6.39	2.89
UEL	0.66	0.34	1.00	1.08	1.52	0.69	6.09	4.39	7.81	3.54

Table 29: 90% CI results from the difference in muscle stimulation across all participants by sensor for Task 3. Green indicates equivalence; red indicates non-equivalence.

Task 3: Hatch										
Sensor	1	2	3	4	5	6	7	8	9	10
Average	0.13	0.05	0.19	0.26	0.35	0.19	1.29	1.93	3.29	1.34
StDev	0.33	0.10	0.45	0.65	0.61	0.55	4.20	11.33	22.67	5.08
Margin of Error	0.07	0.02	0.09	0.14	0.13	0.11	0.88	2.39	4.77	1.07
Lower Limit	0.06	0.03	0.10	0.12	0.22	0.07	0.41	-0.46	-1.48	0.27
Upper Limit	0.20	0.07	0.28	0.39	0.48	0.30	2.18	4.32	8.07	2.41
90% CI	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90
N	61	61	61	61	61	61	61	61	61	61
Equivalence Limits										
Average	0.13	0.05	0.19	0.26	0.35	0.19	1.29	1.93	3.29	1.34
10%	0.01	0.00	0.02	0.03	0.04	0.02	0.13	0.19	0.33	0.13
LEL	0.11	0.04	0.17	0.23	0.32	0.17	1.16	1.74	2.96	1.21
UEL	0.14	0.05	0.21	0.28	0.39	0.21	1.42	2.12	3.62	1.47

Table 30: 90% CI results from the difference in muscle stimulation across all participants by sensor for Task 4. Green indicates equivalence; red indicates non-equivalence.

Task 4: Slider Block										
Sensor	1	2	3	4	5	6	7	8	9	10
Average	0.20	0.08	0.10	0.39	0.15	0.16	1.24	1.43	0.67	0.74
StDev	0.72	0.07	0.10	1.66	0.17	0.45	4.49	6.08	1.78	2.39
Margin of Error	0.15	0.02	0.02	0.35	0.04	0.09	0.94	1.28	0.38	0.50
Lower Limit	0.04	0.06	0.08	0.04	0.11	0.07	0.30	0.15	0.30	0.24
Upper Limit	0.35	0.09	0.12	0.74	0.18	0.26	2.19	2.71	1.05	1.24
90% CI	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90
N	61	61	61	61	61	61	61	61	61	61
Equivalence Limits										
Average	0.20	0.08	0.10	0.39	0.15	0.16	1.24	1.43	0.67	0.74
10%	0.02	0.01	0.01	0.04	0.01	0.02	0.12	0.14	0.07	0.07
LEL	0.18	0.07	0.09	0.35	0.13	0.15	1.12	1.29	0.60	0.67
UEL	0.22	0.08	0.11	0.43	0.16	0.18	1.37	1.57	0.74	0.82

Table 31: 90% CI results from the difference in muscle stimulation across all participants by sensor for Task 5. Green indicates equivalence; red indicates non-equivalence.

Task 5: Replace Hatch										
Sensor	1	2	3	4	5	6	7	8	9	10
Average	0.14	0.07	0.21	0.25	0.37	0.18	1.49	0.45	0.92	0.39
StDev	0.34	0.16	0.60	0.73	0.64	0.52	7.30	1.34	4.59	1.11
Margin of Error	0.07	0.03	0.13	0.15	0.14	0.11	1.54	0.28	0.97	0.23
Lower Limit	0.07	0.04	0.08	0.09	0.24	0.07	-0.05	0.17	-0.05	0.16
Upper Limit	0.21	0.11	0.34	0.40	0.51	0.29	3.03	0.73	1.88	0.62
90% CI	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90
N	61	61	61	61	61	61	61	61	61	61
Equivalence Limits										
Average	0.14	0.07	0.21	0.25	0.37	0.18	1.49	0.45	0.92	0.39
10%	0.01	0.01	0.02	0.02	0.04	0.02	0.15	0.05	0.09	0.04
LEL	0.13	0.06	0.19	0.22	0.34	0.17	1.34	0.41	0.82	0.35
UEL	0.16	0.08	0.23	0.27	0.41	0.20	1.64	0.50	1.01	0.43

Table 32: 90% CI results from the difference in muscle stimulation across all participants by sensor for Task 6. Green indicates equivalence; red indicates non-equivalence.

Task 6: Swivel Knob (2)										
Sensor	1	2	3	4	5	6	7	8	9	10
Average	0.19	0.11	0.30	0.34	0.51	0.21	1.50	0.88	1.22	4.36
StDev	0.25	0.15	0.45	0.59	0.64	0.31	3.23	3.34	4.46	27.86
Margin of Error	0.05	0.03	0.10	0.13	0.14	0.07	0.69	0.71	0.95	5.92
Lower Limit	0.13	0.07	0.21	0.21	0.38	0.14	0.81	0.17	0.27	-1.56
Upper Limit	0.24	0.14	0.40	0.46	0.65	0.27	2.18	1.59	2.17	10.27
90% CI	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90
N	60	60	60	60	60	60	60	60	60	60
Equivalence Limits										
Average	0.19	0.11	0.30	0.34	0.51	0.21	1.50	0.88	1.22	4.36
10%	0.02	0.01	0.03	0.03	0.05	0.02	0.15	0.09	0.12	0.44
LEL	0.17	0.10	0.27	0.30	0.46	0.19	1.35	0.80	1.10	3.92
UEL	0.20	0.12	0.33	0.37	0.56	0.23	1.65	0.97	1.34	4.79

Table 33: 90% CI results from the difference in muscle stimulation across all participants by sensor for Task 7. Green indicates equivalence; red indicates non-equivalence.

Task 7: Cover Plate										
Sensor	1	2	3	4	5	6	7	8	9	10
Average	0.12	0.10	0.13	0.27	0.26	0.25	0.86	1.42	1.27	0.39
StDev	0.13	0.13	0.20	0.66	0.59	0.85	2.08	4.52	6.22	0.90
Margin of Error	0.03	0.03	0.04	0.14	0.12	0.18	0.44	0.95	1.31	0.19
Lower Limit	0.10	0.07	0.09	0.13	0.13	0.07	0.43	0.46	-0.04	0.20
Upper Limit	0.15	0.12	0.18	0.41	0.38	0.43	1.30	2.37	2.58	0.58
90% CI	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90
N	61	61	61	61	61	61	61	61	61	61
Equivalence Limits										
Average	0.12	0.10	0.13	0.27	0.26	0.25	0.86	1.42	1.27	0.39
10%	0.01	0.01	0.01	0.03	0.03	0.02	0.09	0.14	0.13	0.04
LEL	0.11	0.09	0.12	0.25	0.23	0.22	0.78	1.28	1.14	0.35
UEL	0.14	0.11	0.15	0.30	0.28	0.27	0.95	1.56	1.40	0.43

Table 34: 90% CI results from the difference in muscle stimulation across all participants by sensor for Task 8. Green indicates equivalence; red indicates non-equivalence.

Task 8: Cover Bolts										
Sensor	1	2	3	4	5	6	7	8	9	10
Average	0.85	0.89	1.81	3.40	2.83	2.42	14.39	11.00	18.78	8.02
StDev	0.92	1.23	2.10	8.37	3.62	6.72	49.39	36.54	83.09	26.38
Margin of Error	0.19	0.26	0.44	1.76	0.76	1.42	10.40	7.70	17.50	5.55
Lower Limit	0.66	0.63	1.37	1.63	2.07	1.00	3.99	3.31	1.28	2.46
Upper Limit	1.05	1.15	2.25	5.16	3.60	3.84	24.79	18.70	36.28	13.57
90% CI	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90
N	61	61	61	61	61	61	61	61	61	61
Equivalence Limits										
Average	0.85	0.89	1.81	3.40	2.83	2.42	14.39	11.00	18.78	8.02
10%	0.09	0.09	0.18	0.34	0.28	0.24	1.44	1.10	1.88	0.80
LEL	0.77	0.80	1.63	3.06	2.55	2.18	12.95	9.90	16.91	7.22
UEL	0.94	0.98	1.99	3.73	3.12	2.66	15.82	12.10	20.66	8.82

Table 35: 90% CI results from the difference in muscle stimulation across all participants by sensor for Task 9. Green indicates equivalence; red indicates non-equivalence.

Task 9: Lifting Bracket										
Sensor	1	2	3	4	5	6	7	8	9	10
Average	0.10	0.08	0.11	0.31	0.15	0.43	0.83	1.43	0.56	0.99
StDev	0.13	0.18	0.12	0.88	0.19	2.07	2.64	4.73	1.58	3.20
Margin of Error	0.03	0.04	0.02	0.19	0.04	0.44	0.56	1.00	0.33	0.67
Lower Limit	0.07	0.04	0.08	0.12	0.11	-0.01	0.28	0.43	0.23	0.32
Upper Limit	0.13	0.12	0.13	0.49	0.19	0.86	1.39	2.43	0.89	1.66
90% CI	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90
N	61	61	61	61	61	61	61	61	61	61
Equivalence Limits										
Average	0.10	0.08	0.11	0.31	0.15	0.43	0.83	1.43	0.56	0.99
10%	0.01	0.01	0.01	0.03	0.02	0.04	0.08	0.14	0.06	0.10
LEL	0.09	0.07	0.10	0.28	0.14	0.38	0.75	1.29	0.50	0.89
UEL	0.11	0.09	0.12	0.34	0.17	0.47	0.92	1.57	0.62	1.09

Table 36: 90% CI results from the difference in muscle stimulation across all participants by sensor for Task 10. Green indicates equivalence; red indicates non-equivalence.

Task 10: Lifting Bracket Bolts										
Sensor	1	2	3	4	5	6	7	8	9	10
Average	0.42	0.31	0.62	1.53	0.75	1.24	6.66	5.96	5.52	4.74
StDev	0.66	0.36	0.86	4.38	0.95	4.44	33.40	18.22	17.55	19.08
Margin of Error	0.14	0.08	0.18	0.92	0.20	0.93	7.03	3.84	3.70	4.02
Lower Limit	0.29	0.23	0.44	0.61	0.55	0.31	-0.37	2.12	1.82	0.73
Upper Limit	0.56	0.38	0.80	2.46	0.95	2.18	13.69	9.80	9.21	8.76
90% CI	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90
N	61	61	61	61	61	61	61	61	61	61
Equivalence Limits										
Average	0.42	0.31	0.62	1.53	0.75	1.24	6.66	5.96	5.52	4.74
10%	0.04	0.03	0.06	0.15	0.08	0.12	0.67	0.60	0.55	0.47
LEL	0.38	0.28	0.56	1.38	0.68	1.12	5.99	5.36	4.96	4.27
UEL	0.47	0.34	0.68	1.69	0.83	1.37	7.33	6.56	6.07	5.22

Table 37: 90% CI results from the difference in muscle stimulation across all participants by sensor for Task 11. Green indicates equivalence; red indicates non-equivalence.

Task 11: Rotate (1)										
Sensor	1	2	3	4	5	6	7	8	9	10
Average	0.05	0.03	0.10	0.33	0.18	0.27	0.38	0.82	0.69	0.55
StDev	0.06	0.03	0.17	1.18	0.38	0.98	1.09	2.99	3.53	2.35
Margin of Error	0.01	0.01	0.04	0.25	0.08	0.21	0.23	0.63	0.74	0.50
Lower Limit	0.04	0.02	0.06	0.08	0.10	0.07	0.15	0.19	-0.05	0.06
Upper Limit	0.06	0.04	0.13	0.58	0.26	0.48	0.61	1.45	1.44	1.05
90% CI	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90
N	61	61	61	61	61	61	61	61	61	61
Equivalence Limits										
Average	0.05	0.03	0.10	0.33	0.18	0.27	0.38	0.82	0.69	0.55
10%	0.00	0.00	0.01	0.03	0.02	0.03	0.04	0.08	0.07	0.06
LEL	0.04	0.03	0.09	0.30	0.16	0.25	0.34	0.74	0.62	0.50
UEL	0.05	0.03	0.11	0.36	0.19	0.30	0.41	0.90	0.76	0.61

Table 38: 90% CI results from the difference in muscle stimulation across all participants by sensor for Task 12. Green indicates equivalence; red indicates non-equivalence.

Task 12: Card										
Sensor	1	2	3	4	5	6	7	8	9	10
Average	0.09	0.04	0.10	0.32	0.18	0.32	0.72	1.03	0.31	0.64
StDev	0.10	0.05	0.09	1.34	0.19	1.19	2.74	5.52	0.62	2.15
Margin of Error	0.02	0.01	0.02	0.29	0.04	0.26	0.59	1.18	0.13	0.46
Lower Limit	0.07	0.03	0.09	0.03	0.14	0.06	0.14	-0.15	0.17	0.18
Upper Limit	0.11	0.05	0.12	0.61	0.22	0.57	1.31	2.21	0.44	1.10
90% CI	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90
N	59	59	59	59	59	59	59	59	59	59
Equivalence Limits										
Average	0.09	0.04	0.10	0.32	0.18	0.32	0.72	1.03	0.31	0.64
10%	0.01	0.00	0.01	0.03	0.02	0.03	0.07	0.10	0.03	0.06
LEL	0.08	0.03	0.09	0.29	0.16	0.29	0.65	0.93	0.28	0.58
UEL	0.10	0.04	0.11	0.35	0.20	0.35	0.80	1.13	0.34	0.71

Table 39: 90% CI results from the difference in muscle stimulation across all participants by sensor for Task 13. Green indicates equivalence; red indicates non-equivalence.

Task 13: Rotate (2)										
Sensor	1	2	3	4	5	6	7	8	9	10
Average	0.05	0.03	0.08	0.46	0.10	0.35	0.51	0.44	0.97	0.19
StDev	0.05	0.03	0.08	1.94	0.12	1.45	2.18	1.24	5.36	0.46
Margin of Error	0.01	0.01	0.02	0.43	0.03	0.32	0.48	0.27	1.18	0.10
Lower Limit	0.04	0.03	0.06	0.03	0.08	0.03	0.03	0.17	-0.21	0.09
Upper Limit	0.06	0.04	0.09	0.89	0.13	0.66	0.99	0.71	2.15	0.29
90% CI	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90
N	56	56	56	56	56	56	56	56	56	56
Equivalence Limits										
Average	0.05	0.03	0.08	0.46	0.10	0.35	0.51	0.44	0.97	0.19
10%	0.01	0.00	0.01	0.05	0.01	0.03	0.05	0.04	0.10	0.02
LEL	0.05	0.03	0.07	0.41	0.09	0.31	0.46	0.40	0.87	0.17
UEL	0.06	0.04	0.08	0.51	0.12	0.38	0.56	0.49	1.06	0.21

Table 40: 90% CI results from the difference in muscle stimulation across all participants by sensor for Task 14. Green indicates equivalence; red indicates non-equivalence.

Task 14: Threaded Shaft										
Sensor	1	2	3	4	5	6	7	8	9	10
Average	0.15	0.18	0.41	5.08	0.39	0.78	2.92	3.02	2.13	1.73
StDev	0.23	0.34	0.74	33.24	0.41	2.63	7.50	11.29	10.68	7.72
Margin of Error	0.05	0.07	0.16	7.18	0.09	0.57	1.62	2.44	2.31	1.67
Lower Limit	0.10	0.10	0.25	-2.10	0.30	0.21	1.30	0.58	-0.18	0.07
Upper Limit	0.20	0.25	0.57	12.26	0.48	1.35	4.54	5.46	4.44	3.40
90% CI	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90
N	58	58	58	58	58	58	58	58	58	58
Equivalence Limits										
Average	0.15	0.18	0.41	5.08	0.39	0.78	2.92	3.02	2.13	1.73
10%	0.02	0.02	0.04	0.51	0.04	0.08	0.29	0.30	0.21	0.17
LEL	0.14	0.16	0.37	4.57	0.35	0.70	2.63	2.72	1.92	1.56
UEL	0.17	0.19	0.45	5.58	0.43	0.86	3.21	3.32	2.34	1.91

Dtrack

Dtrack Descriptive Statistics

While ART does have a fluid data capture software available, this study did not have access to it. This unfortunately turned an intended dynamic data analysis static. That said, an instance-in-time methodology was applied for this data extraction. Seven instances in time were selected to have the X, Y, and Z coordinates documented for each of the 4 body IDs (glasses, lower right arm, lower left arm, and sternum). See Figure 49 for an explanation of which directions X, Y, and Z were in the workspace. These seven instances were a subset of the same static assessments performed in the REBA and RULA assessments and consisted of the following part installations: slider block, cover plate, cover plate bolts, lifting bracket, lifting bracket bolts, card, and threaded shaft. The housing pick was left out as the Dtrack system was unable to capture those data points as the table used for the PEAT base starting point was outside of the Dtrack cameras' viewpoints.

The system was calibrated in roughly the center of the room on the floor, roughly 3 feet back from the assembly workbench. These position values provided a 3D point in space presented in millimeters ranging from -1171.11 to 1776.81 in value. A negative value in this case is simply representative of a data point that was in the negative direction from the data set by the system calibration. The equivalence testing methodology does not work well with negative numbers, as it confuses the upper equivalence limit (UEL) and lower equivalence limit (LEL). For this purpose, we normalized the data to fit within a scaled range of 0-100 by using the formula below. The summary statistics for both the raw and normalized data can be found in the Dtrack Equivalence Testing section. Box plots utilizing the raw data for each of the assessed positions can be found in Figure 50 through Figure 56.

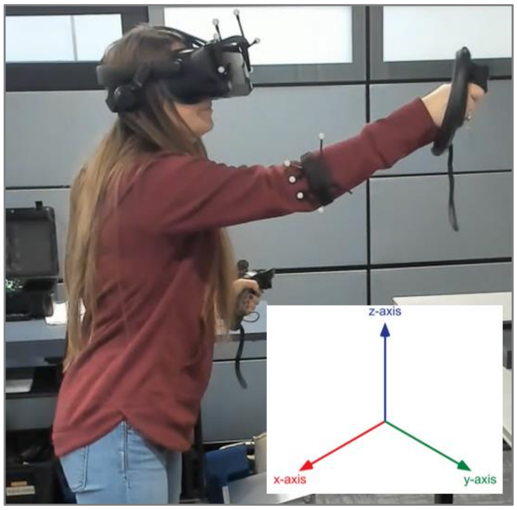


Figure 49: X, Y, Z directions for room explained.
Image source for 3D axis: https://images.app.goo.gl/RUSHrRmgnuQpRGVJ9

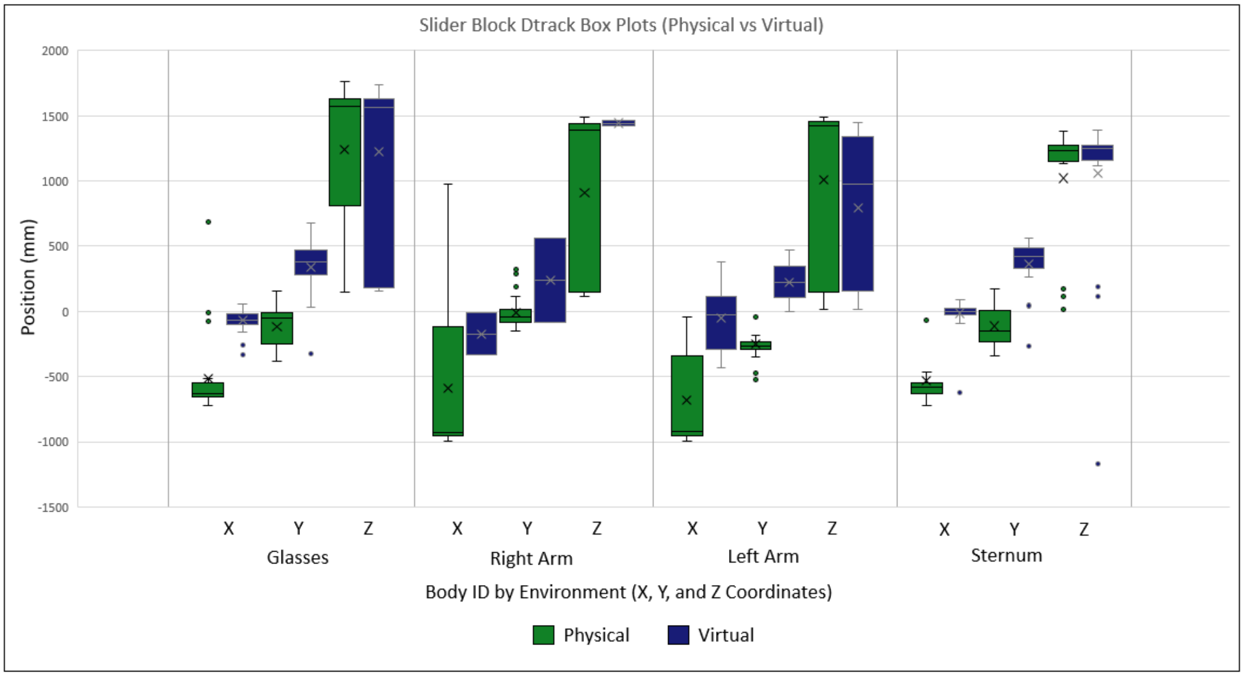


Figure 50: Dtrack slider block assessment box plots (physical vs virtual) by body ID

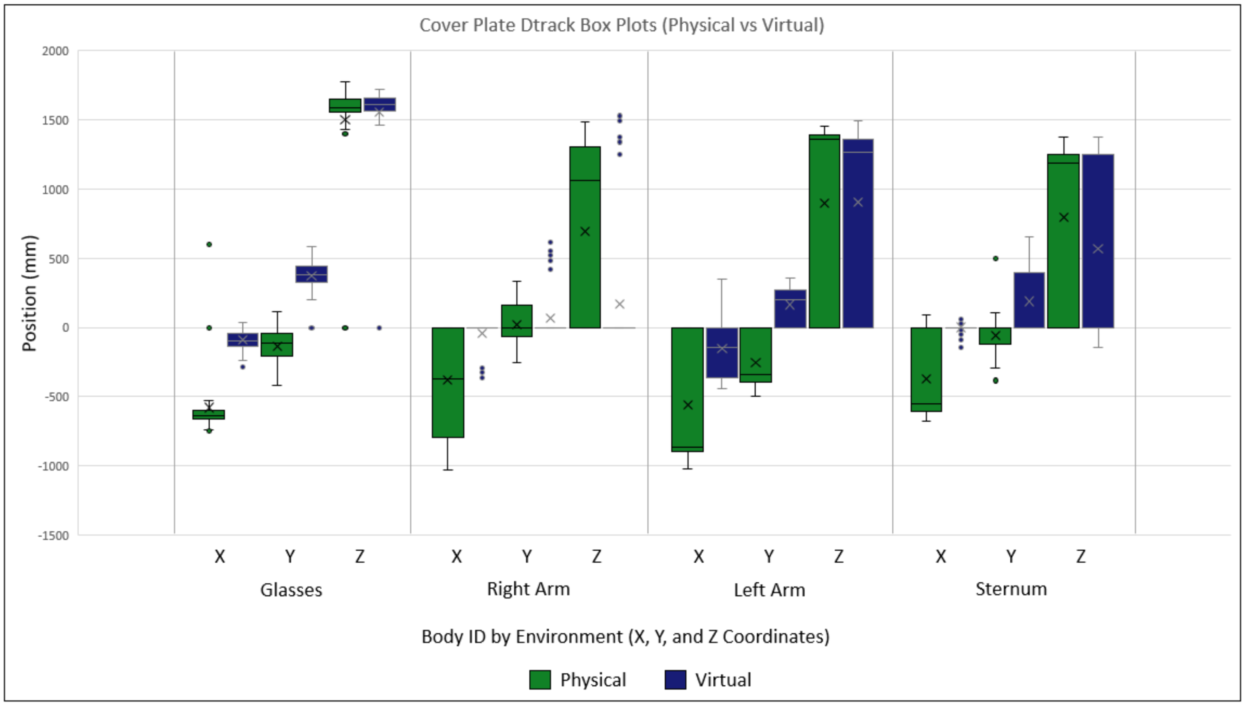


Figure 51: Dtrack cover plate assessment box plots (physical vs virtual) by body ID

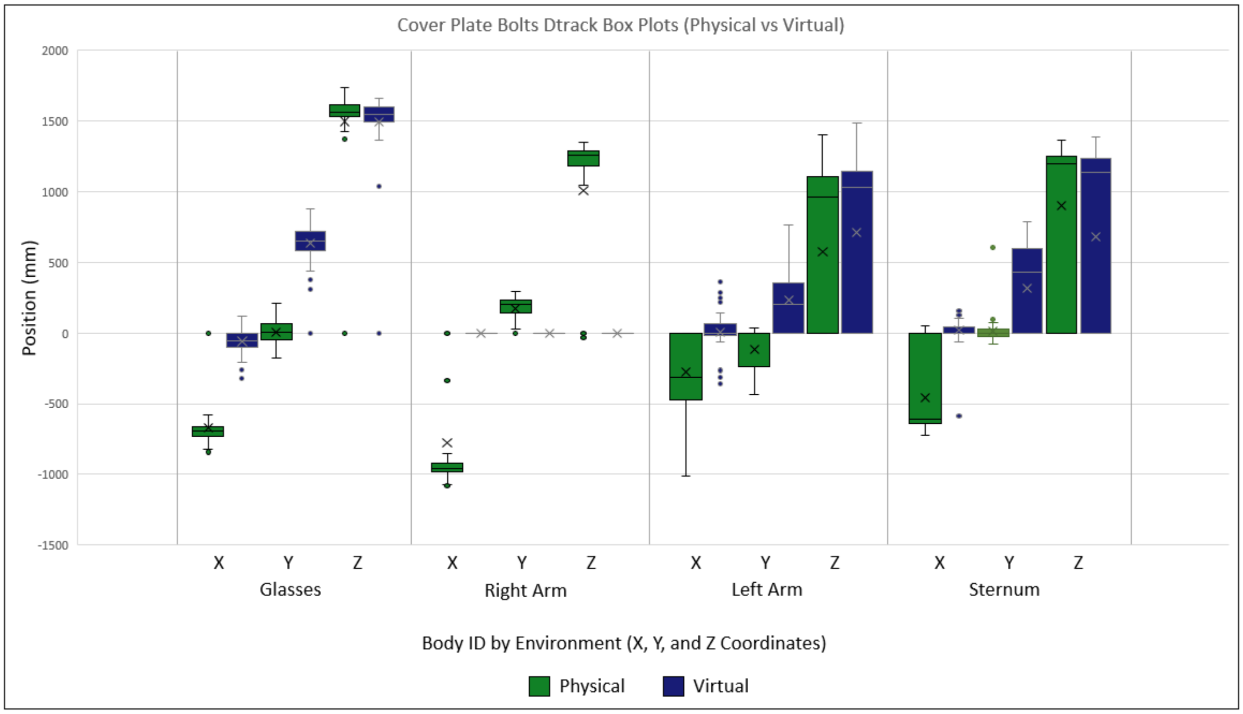


Figure 52: Dtrack cover plate assessment box plots (physical vs virtual) by body ID

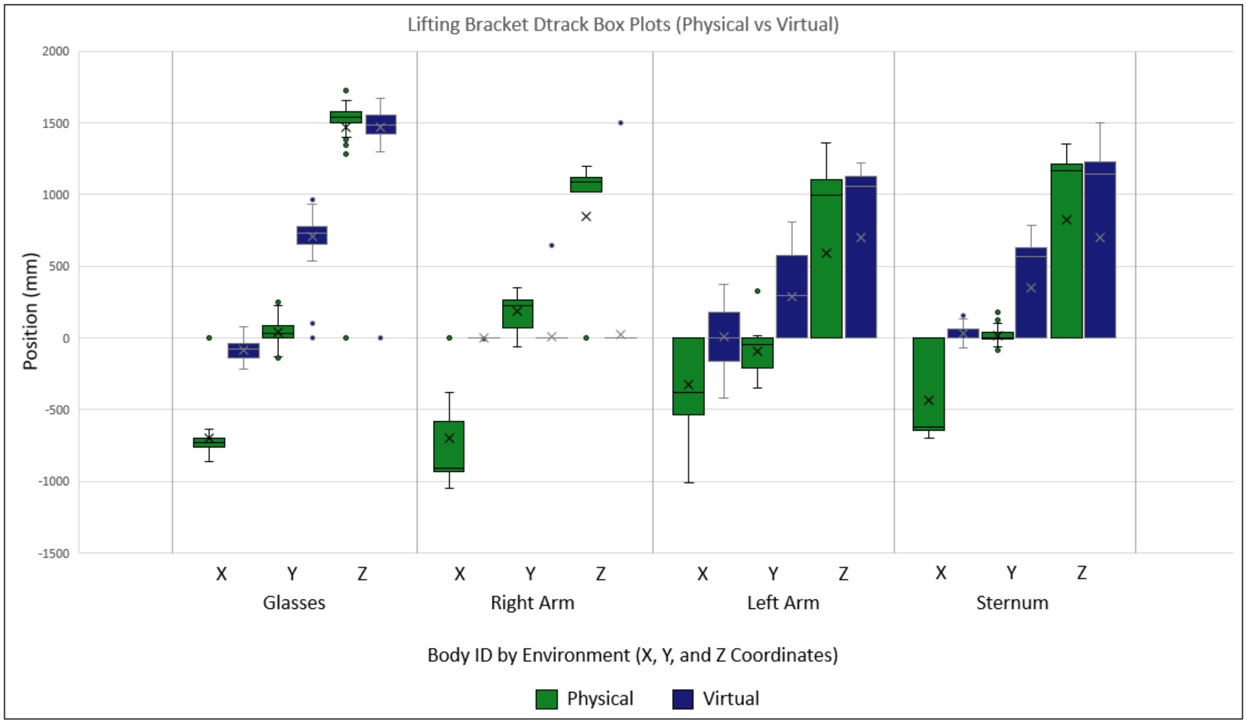


Figure 53: Dtrack lifting bracket assessment box plots (physical vs virtual) by body ID

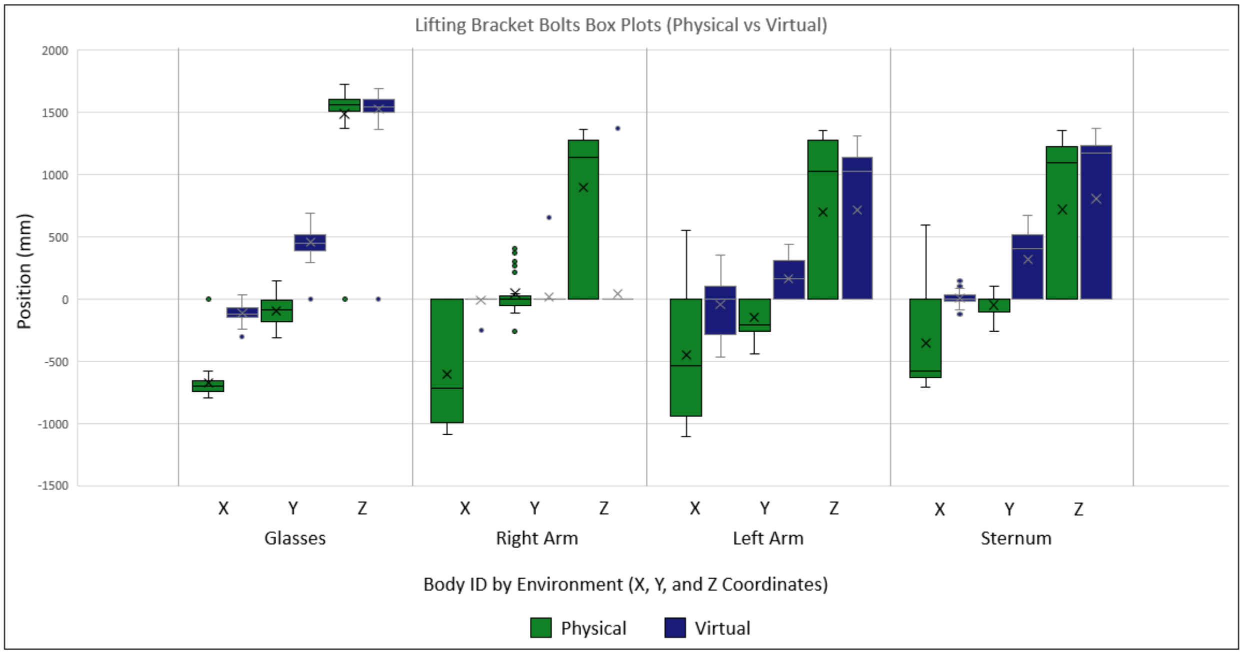


Figure 54: Dtrack lifting bracket bolts assessment box plots (physical vs virtual) by body ID

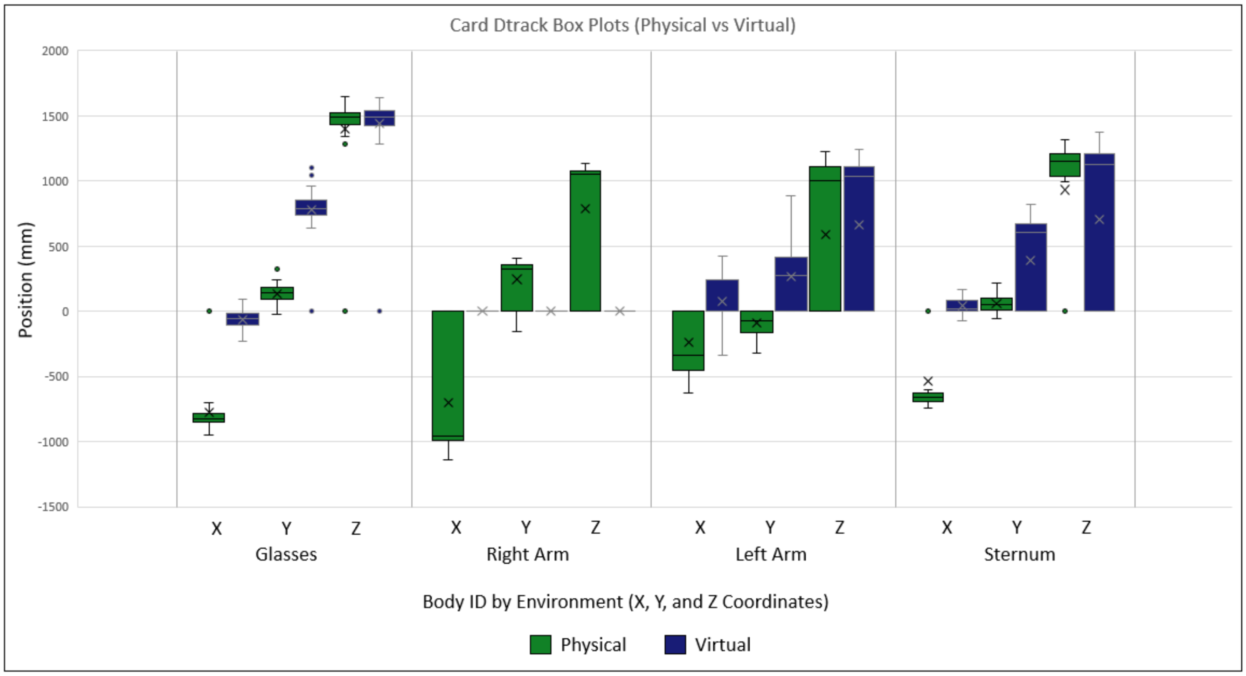


Figure 55: Dtrack card assessment box plots (physical vs virtual) by body ID

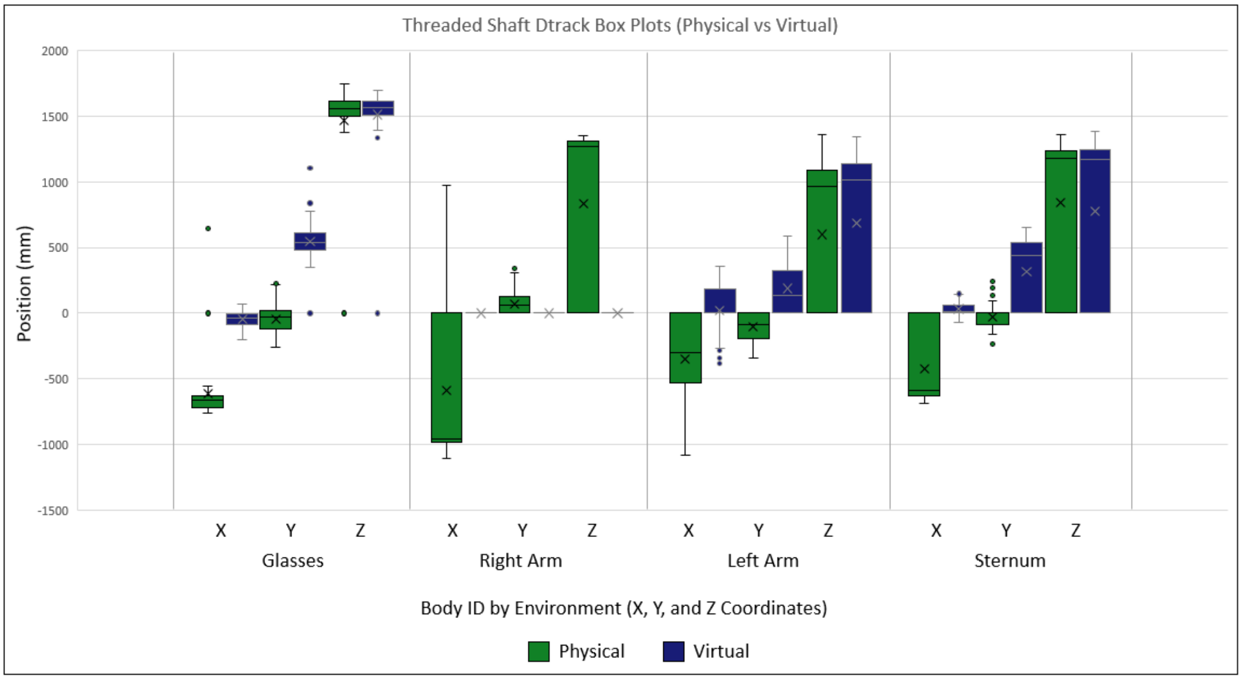


Figure 56: Dtrack threaded shaft assessment box plots (physical vs virtual) by body ID

As stated earlier, While Dtrack does have a fluid data capture software available, this study did not have access to it. That said, an instance-in-time methodology was applied for this data extraction. Additionally, the cameras utilized to track the motion tracker balls that provided the positional data remained in a fixed overhead position. When several motion tracker balls of an ID were obstructed, the system was unable to capture a value. This could be caused by situations such as a participant bending over with their arms in front of them, obstructing the cameras line of site. It is important to consider that due to the positional analysis, this resulted in some data gaps. With a fluid data capture, more data likely would have been available, but due to these circumstances, a different number of data points were captured for each body ID. Figure 57 displays a graphical representation of the number of data points captured by each body ID in each environment. It is clear that the largest gap in data we see is in the right arm of the virtual environment. This is likely due to a majority of the participants opting to use the left controller, resulting in their right arm remaining in a neutral position. This phenomenon, coupled with the virtual reality rendering being back a few feet from the work bench resulted in further obstruction of the cameras line of sight result in very few data points.

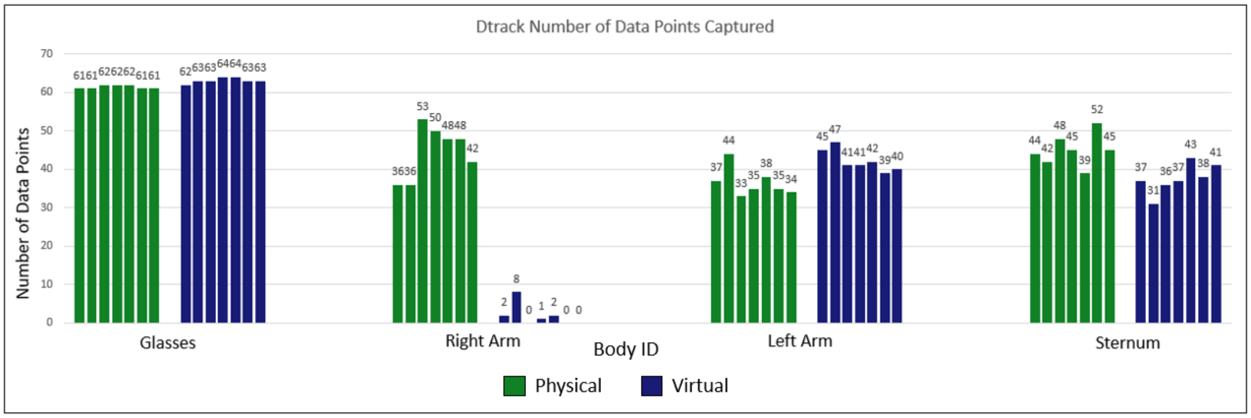


Figure 57: Dtrack number of data points captured by body ID in both the physical and virtual environment.

Dtrack Equivalence Testing

As stated, equivalence testing has difficulty interpreting negative values. It is for this reason the data was normalized to fit a 0-100 scale. This would contain the magnitude of each value while allowing the data to be analyzed from an equivalence testing perspective. This normalization was performed using the following formula:

$$X - \frac{Min\,V}{Range\ of\ V} * 100$$

Where:

X – value to be normalized

V – column of X, Y or Z being analyzed

Table 41 provides a breakdown for each respective position number. Table 42 through Table 45 display both the raw positional data (in mm) as well as the normalized data utilized for the equivalence testing. These values represent the average position in the X, Y, and Z directions for each position in time.

Table 41: Position number reference table for Dtrack normalized values.

Position	Position #
Slider Block	1
Cover Plate	2
Cover Plate Bolts	3
Lifting Bracket	4
Lifting Bracket Bolts	5
Card	6
Threaded Shaft	7

Table 42: Dtrack raw vs normalized data for glasses body ID tracking. R- raw data, N- normalized data

	Glasses Physical						Glasses Virtual					
Position	R-X	R-Y	R-Z	N-X	N-Y	N-Z	R-X	R-Y	R-Z	N-X	N-Y	N-Z
1	-513.4	-114.0	1241.9	14.6	49.8	67.6	-69.0	339.2	1226.7	67.4	66.3	67.6
2	-541.1	-117.8	1314.3	15.3	56.6	73.7	-75.3	318.0	1253.3	66.0	52.6	72.7
3	-570.6	2.5	1345.2	32.5	56.6	75.3	-46.1	583.8	1218.5	62.1	63.9	73.2
4	-606.8	41.7	1199.3	32.1	46.3	69.2	-67.7	674.2	1201.9	50.7	11.2	71.8
5	-560.9	-71.5	1424.6	31.8	49.8	80.9	-96.9	389.0	1353.7	60.1	55.9	78.0
6	-700.5	123.8	1160.6	28.7	54.7	67.6	-48.0	675.9	1237.7	54.8	68.4	73.1
7	-614.1	-47.6	1332.5	10.2	43.8	74.0	-35.0	435.2	1261.1	63.4	48.6	75.5

Table 43: Dtrack raw vs normalized data for right arm body ID tracking.

	Right Arm Physical						Right Arm Virtual					
Position	R-X	R-Y	R-Z	N-X	N-Y	N-Z	R-X	R-Y	R-Z	N-X	N-Y	N-Z
1	-588.2	-9.6	910.6	20.6	29.6	57.9	-173.3	238.8	1443.6	50.0	50.0	50.0
2	-564.2	10.5	718.1	44.6	45.8	46.5	-325.7	474.5	1382.0	75.2	74.7	46.3
3	-752.0	163.9	1007.9	24.6	55.7	75.2						
4	-726.4	186.7	465.6	27.6	69.4	38.2	-6.4	642.4	1496.7			
5	-471.9	44.8	852.0	53.2	46.8	58.9	-138.8	657.7	695.3	50.0	50.0	
6	-609.3	261.3	268.9	46.8	77.5	22.8						
7	-652.8	86.6	1044.6	18.3	24.0	75.0						

Table 44: Dtrack raw vs normalized data for left arm body ID tracking.

	Left Arm Physical						Left Arm Virtual					
Position	R-X	R-Y	R-Z	N-X	N-Y	N-Z	R-X	R-Y	R-Z	N-X	N-Y	N-Z
1	-679.6	-251.3	1008.6	33.4	54.4	67.5	-48.0	224.5	792.9	47.2	48.2	54.4
2	-727.9	-308.2	1026.5	25.5	40.2	70.7	-155.3	196.8	1012.4	36.5	55.1	66.2
3	-450.1	-180.3	650.9	55.7	53.7	41.8	-5.9	240.3	547.9	54.7	31.0	36.4
4	-494.4	-110.9	559.1	53.0	28.8	40.8	-8.7	323.9	618.3	51.9	40.0	50.4
5	-613.6	-216.6	779.2	24.4	41.8	57.1	-48.3	196.3	584.5	50.6	44.2	46.2
6	-409.4	-136.7	492.8	36.3	52.3	39.7	78.3	364.9	502.8	54.7	39.0	34.5

Table 44 Continued

	Left Arm Physical						Left Arm Virtual					
Position	R-X	R-Y	R-Z	N-X	N-Y	N-Z	R-X	R-Y	R-Z	N-X	N-Y	N-Z
7	-511.5	-172.2	766.7	48.9	50.3	55.9	28.3	287.2	603.0	55.5	47.0	44.3

Table 45: Dtrack raw vs normalized data for sternum body ID tracking.

	Sternum Physical						Sternum Virtual					
Position	R-X	R-Y	R-Z	N-X	N-Y	N-Z	R-X	R-Y	R-Z	N-X	N-Y	N-Z
1	-528.8	-113.7	1021.3	29.4	44.3	73.9	-14.5	360.0	1060.9	85.0	75.2	87.2
2	-486.7	-77.5	1087.6	24.6	34.7	77.1	-1.5	297.3	987.5	62.7	39.3	74.3
3	-484.7	5.6	887.9	30.7	36.1	63.4	28.6	472.8	961.0	79.6	57.7	68.0
4	-549.7	16.0	847.2	22.4	39.7	62.2	157.6	541.2	880.1	5.0	66.2	56.9
5	-518.3	-68.2	918.5	13.6	58.7	67.4	10.1	380.4	944.1	48.7	56.1	68.4
6	-568.4	57.6	902.7	25.3	42.3	68.4	46.2	548.3	956.1	49.8	64.3	67.6
7	-442.2	-32.0	955.0	40.3	42.3	68.7	45.0	431.5	1043.0	53.3	63.7	73.1

Similar to the Delsys analysis, a 90% confidence interval for equivalence testing was performed here to indicate the presence of equivalence. Table 46 displays the summarized results for Dtrack equivalence testing by body ID in the X, Y and Z directions. The individual analysis for each body ID in each direction can be found in Table 47 through Table 50. As the tables display, equivalence was deemed in all Z directions, and two of the four Y directions. The largest exception to this would be the right arm analysis. These results were largely due again to participants generally opting to utilize the left controller due to its better responsiveness. That said, it is promising to see that in all directions from a 3D point in space perspective the left arm was equivalent in all directions. Considering a majority of the virtual assemblies were completed with the left controller this result has strong implications for ergonomic assessment. The largest struggle seen from this positional analysis is in the X direction. This is likely due to the virtual reality HMD having to be calibrated a few feet away from the assembly bench in the X direction to avoid participants coming into contact with the physical workbench during part reaches in the virtual environment. Equivalence in the Z direction indicates that the virtual environment was scaled correctly to the physical environment.

Table 46: Dtrack equivalence testing summary table by body ID in X, Y, and Z directions

Coordinate	Glasses	Right Arm	Left Arm	Sternum
X	No	No	Yes	No
Y	No	No	Yes	Yes
Z	Yes	No	Yes	Yes

Table 47: Dtrack equivalence testing results summary by glasses in X, Y, and Z directions

Glasses			
Variable	X	Y	Z
Average	42.12	51.76	72.87
Standard Deviation	20.74	13.77	3.96
Margin of Error	4.56	3.03	0.87
Lower Limit	37.56	48.73	72.01
Upper Limit	46.68	54.79	73.74
90% CI	0.90	0.90	0.90
N	56.00	56.00	56.00
Equivalence Limits			
Average	42.12	51.76	72.87
10%	4.21	5.18	7.29
LEL	37.91	46.58	65.59
UEL	46.33	56.93	80.16

Table 48: Dtrack equivalence testing results summary by right arm in X, Y, and Z directions

Right Arm			
Variable	X	Y	Z
Average	41.09	52.34	52.33
Standard Deviation	17.97	17.78	16.81
Margin of Error	9.34	9.34	9.85
Lower Limit	31.74	43.00	42.48
Upper Limit	50.43	61.69	62.18
90% CI	0.9	0.9	0.9
N	10	10	9
Equivalence Limits			
Average	41.09	52.34	52.33
10%	4.11	5.23	5.23
LEL	36.98	47.11	47.09
UEL	45.2	57.58	57.56

Table 49: Dtrack equivalence testing results summary by left arm in X, Y, and Z directions

Left Arm			
Variable	X	Y	Z
Average	44.89	44.71	50.42
Standard Deviation	11.32	8.39	11.86
Margin of Error	2.49	1.84	2.61
Lower Limit	42.40	42.87	47.81
Upper Limit	47.38	46.56	53.03
90% CI	0.9	0.9	0.9
N	56	56	56
Equivalence Limits			
Average	44.89	44.71	50.42
10%	4.49	4.47	5.04
LEL	40.40	40.24	45.38
UEL	49.38	49.18	55.46

Table 50: Dtrack equivalence testing results summary by sternum in X, Y, and Z directions

Sternum			
Variable	X	Y	Z
Average	40.75	51.47	69.75
Standard Deviation	23.76	13.10	7.28
Margin of Error	5.22	2.88	1.60
Lower Limit	35.52	48.59	68.15
Upper Limit	45.97	54.36	71.35
90% CI	0.9	0.9	0.9
N	56	56	56
Equivalence Limits			
Average	40.75	51.47	69.75
10%	4.07	5.15	6.98
LEL	36.67	46.33	62.78
UEL	44.82	56.62	76.73

Research Question 3

Research question three looked to investigate if younger participants would have a lower task cycle time in virtual reality than older participants. The total number of participants in the study was 65. Of these 65 participants, 49 (75%) identified as male, and 16 (25%) identified as female. Figure 58 displays the age ranges of participants, with the largest age group falling between 18 and 21 years of age. This is largely based on the fact that this research was a university study and the recruitment materials being sent primarily to students.

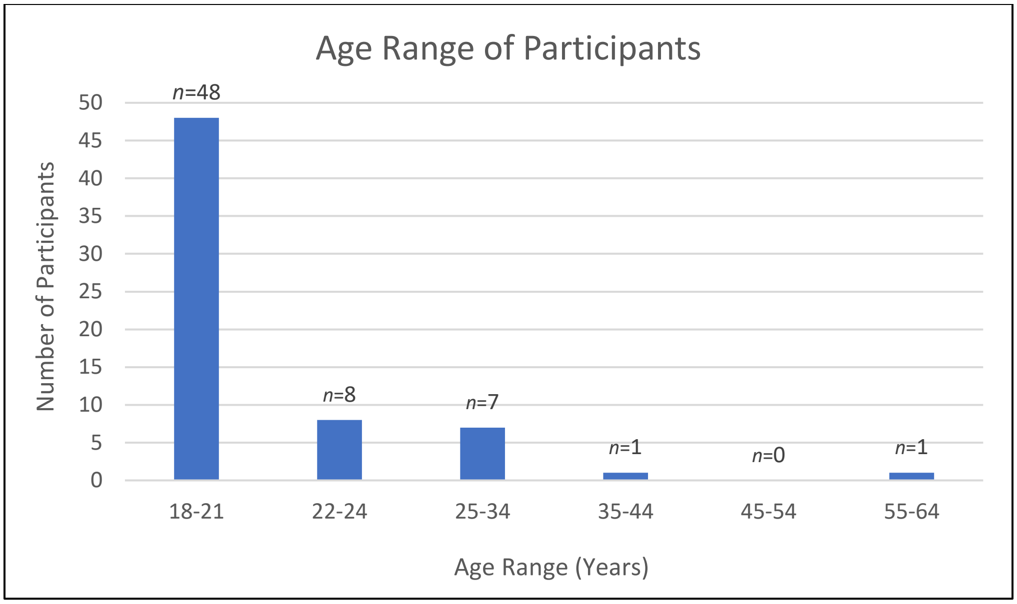


Figure 58: Age Range of Participants

A regression analysis was performed in Excel to see if there was a correlation between participant age and assembly cycle time in the virtual reality environment. Table 51 displays these regression statistics. The “Multiple R” value is the correlation coefficient and measures the strength of the linear relationship between these two variables. Correlation coefficients with magnitude of 0.9 to 1.0 indicate very high correlation, 0.7-0.9 indicate high correlation, 0.5 to 0.7 indicate moderate correlation, 0.3 to 0.5 low correlation, and finally 0.3 and below to be negligible correlation [31]. In this case, the correlation coefficient is .007, indicating almost no relationship at all. This validated our prediction that age would not have an impact on virtual reality cycle time. It is also important to note that only 62 observations were utilized for this analysis. While all participants did report age, there was not a virtual reality cycle time recorded for every participant.

Table 51: RQ3 regression analysis results: age vs virtual reality cycle time

Regression Statistics Age vs VR Cycle Time	
Multiple R	0.007
R Square	0.000
Adjusted R Square	-0.017
Standard Error	6.717
Observations	62.000

Research Question 4

RQ4 investigated whether participants with prior virtual reality experience performed movements in VR that more closely mirrored those in the physical environment than those with less virtual reality experience. In a pre-study survey, participants were asked "Have you had any exposure to virtual reality" with response options of no exposure, some exposure, regular exposure, extensive exposure, and prefer not to say. Table 52 display the summative results of this survey.

Table 52: VR exposure reported results.

VR Exposure	
None	13
Some	35
Regular	11
Extensive	6
Prefer not to say	0
Total	65

Considering that HumanTech was the only tool that produced consistent and repeatable metrics in both the physical and virtual environment, allowing for the true declaration of being a feasible tool to use in a physical and virtual environment, the HumanTech results were used for this correlation analysis. A regression analysis was performed to assess the correlation (if any) between the difference in physical and virtual HumanTech risk scores in relation to participants reported exposure level to virtual reality. With a 100% response rate, Table 53 displays the results of the regression analysis, indicating no correlation between VR exposure and ergonomic risk score repeatability (Multiple R = 0.0362).

Table 53: Regression analysis statistics for risk score repeatability vs VR exposure

Regression Statistics Risk Score Repeatability vs VR Exposure	
Multiple R	0.0362
R Square	0.00131
Adjusted R Square	-0.0148
Standard Error	3.11815
Observations	64

Research Question 5

RQ5 assessed whether those with prior manufacturing experience performed movements in virtual reality that more closely mirrored movements in the physical world than those with little to no manufacturing experience. Participants were asked “Have you had any exposure to a manufacturing/assembly environment?”, however instead of a Likert style answer, this question was left as on open field text in an attempt to not influence the participant and to capture a different perspective than that of RQ4. If a participant explicitly indicated “No” in some capacity or didn’t put anything in the field, it was considered a no. If a participant indicated any sort of an answer implying exposure to manufacturing in some capacity it was considered a yes. In total, 29 participants indicated they had manufacturing experience in some capacity, while 36 indicated they did not. This question did have a 100% response rate.

As with RQ4, a regression analysis was performed comparing the difference in HumanTech scores alongside participant indication of manufacturing exposure. Once again, there is no notable correlation between having manufacturing experience and more repeatable metrics between the physical and virtual environments (Multiple R = 0.0809).

Table 54: Regression analysis statistics for risk score repeatability vs manufacturing exposure

Regression Statistics Manufacturing Exposure vs Risk Score Repeatability	
Multiple R	0.08
R Square	0.00
Adjusted R Square	-0.00
Standard Error	0.50
Observations	65

Research Question 6

RQ6 investigated whether participants who were more active would in turn will have lower REBA and RULA scores. The assumption behind this research question is that those who are more active in their daily lives and who are used to partaking in correct bodily "form" reflect that muscle memory in the assembly environment. In the pre-study survey participants were asked "How many days on average/week are you physically active?" with response options consisting of 0 days, 1-3 days, 4-6 days, 7 days, and prefer not to say. The raw results from this survey question are displayed in Table 55.

Table 55: Summary of participant reported activity levels.

Physical Activity	# of Participants
0 days	1
1-3 days	24
4-6 days	31
7 days	8
Prefer not to say	1

For the regression analysis, these ranges were converted to activity Levels 1-4 to allow for numeric comparison (see Table 56).

Table 56: Assigned activity level key for regression analysis.

Activity Level	Physical Activity
Level 1	0 days
Level 2	1-3 days
Level 3	4-6 days
Level 4	7 days

Considering that REBA/RULA scores are a positional based assessment, and this study analyzed 8 individual postures, the total cumulative REBA and RULA scores for each participant were summed in order to compare to participant activity level. This provided an average cumulative total REBA and RULA score of 29 per participant across all activities. Regression analyses were performed on both the REBA and RULA results compared to participant reported activity level. Table 57 displays the regression statistics for the REBA correlation, while Table 58 displays the regression statistics for the RULA correlation analysis. Only 64 observations were noted as one participant did select “prefer not to say”. Both values are below 0.3 indicating negligible correlation, implying that for this study, participants’ reported activity level did not have an effect on ergonomic risk score.

Table 57: Regression analysis for participant reported activity level vs cumulative REBA score.

Regression Statistics (REBA)	
Multiple R	0.06708
R Square	0.0045
Adjusted R Square	-0.0116
Standard Error	0.7048
Observations	64

Table 58: Regression analysis for participant reported activity level vs cumulative RULA score.

Regression Statistics (RULA)	
Multiple R	0.0496
R Square	0.00246
Adjusted R Square	-0.0136
Standard Error	0.70552
Observations	64

Research Question 7

RQ7 explored performance differences based on handedness. In the pre-study survey participants were asked if they were left or right-handed. This question was asked due to the nature of the interaction design in this particular VR simulation of PEAT assembly (see Figure 11). Of the 65 total participants in this study, 59 reported as right-handed, three reported as left-handed, and three reported as ambidextrous. As stated in multiple instances throughout this paper, during data collection, participants verbally reported issues with feedback on the right controller. For this reason, it was assumed that right-handed participants would have a higher cycle time than those who are left-handed. For the regression analysis, participants who were right-handed were assigned a “1,” participants who were right handed were assigned a “2,” and participants who were ambidextrous were assigned a “3.” It should be noted that while all participants did report their respective handedness, three participants did not have a virtual reality cycle time recorded so those values were excluded from the analysis. A regression analysis compared these assigned values with that of the virtual reality cycle time. As displayed in Table 59, handedness did not have any impact on virtual reality cycle time (Multiple R = 0.18444).

Table 59: Regression analysis for handedness vs virtual reality cycle time

Regression Statistics Handedness vs VRCT	
Multiple R	0.18
R Square	0.03
Adjusted R Square	0.01
Standard Error	0.40
Observations	61

Research Question 8

RQ8 explored whether participants believed PEAT was easier to assemble in the physical or virtual environment. Immediately following each assembly environment, participants were asked “How difficult was it to assemble the product?” with response options consisting of extremely difficult, somewhat difficult, neither easy nor difficult, somewhat easy, extremely easy, and prefer not to say. This survey was given immediately following each assembly experience in an attempt to isolate each experience. Table 60 and Figure 59 display the results from this survey in both the physical and virtual environments. It is clear that participants perceived the virtual version of PEAT proved to be much more difficult to assemble than the physical version. This question also had a 100% response rate from participants in both environments totaling 65 participants in each assessment. This resulted aligned with the predicted result for this research question.

Table 60: Physical vs virtual self-reported PEAT assembly difficulty

Difficulty	Physical	Virtual
Extremely difficult	0	4
Somewhat difficult	1	36
Neither easy nor difficult	2	8
Somewhat easy	20	13
Extremely easy	42	4

Table 60 Continued

Difficulty	Physical	Virtual
Prefer not to say	0	0
Total	65	65

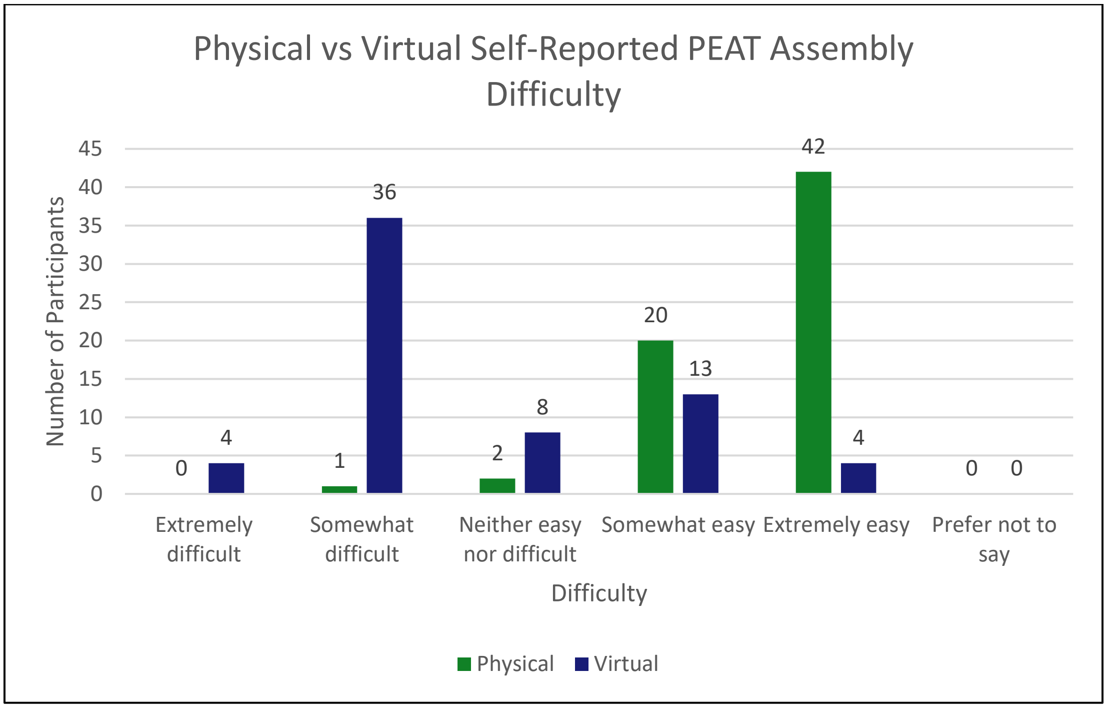


Figure 59: Graphical representation of physical vs virtual self-reported PEAT assembly difficulty

Research Question 9

Within the physical and virtual study surveys (the same surveys referenced in RQ8), participants were asked "Did you experience any ergonomic (comfortable/safe working conditions) discomfort?" with response options of a simple yes, no, or prefer not to answer. Table 61 and Figure 60 display the results of this survey. This question did have a 100% response rate resulting in 65 total participant responses. More participants did report ergonomic discomfort in the virtual environment. This does provoke a question regarding if participants reported a higher ergonomic discomfort in virtual reality due to the novel and frustrating interface (due to difficult small part interactions), or if they genuinely felt more discomfort.

Table 61: Physical vs virtual self-reported ergonomic discomfort

Discomfort	Physical	Virtual
Yes	5	23
No	60	42
Prefer not to say	0	0
Total	65	65

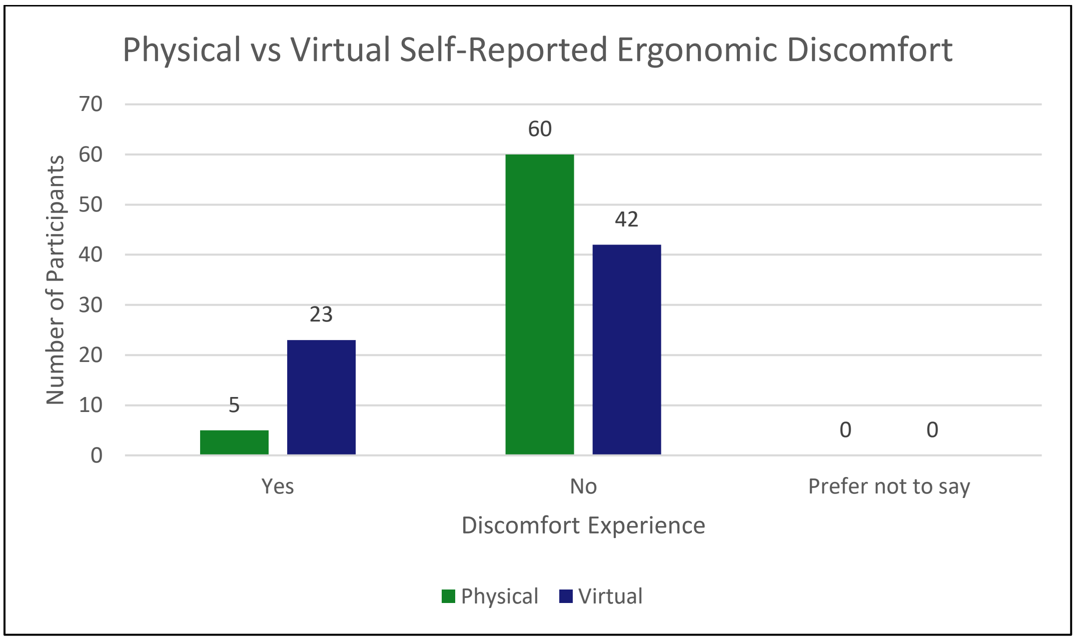


Figure 60: Graphical representation of physical vs virtual self-reported ergonomic discomfort results

Research Question 10

RQ10 addressed the question “Did participant height have an impact on ergonomic risk score result?” Figure 61 displays the height range of participants, with a mean of 69 inches (5’9”) with a standard deviation of 3.5 inches.

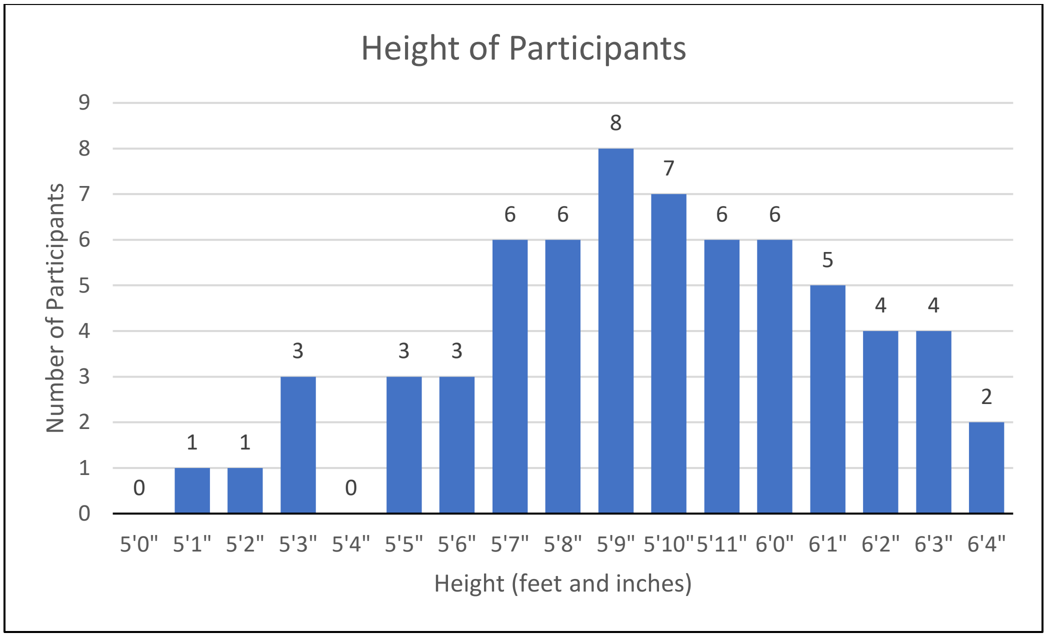


Figure 61: Height of participants

The PEAT assembly workbench was set at a height of 36”. Again, using the cumulative 8 position REBA and RULA scores, as well as the continuous HumanTech score, a regression analysis was ran to assess if height and ergonomic risk score were correlated. Regression statistics results are displayed in Table 62 through Table 64. While these are the highest correlation values this study has seen, these values are still too small to imply strong correlation, indicating no relationship between height and ergonomic risk for this study.

Table 62: Regression analysis results for height vs REBA score.

Regression Statistics Height vs REBA	
Multiple R	0.22
R Square	0.04
Adjusted R Square	0.03
Standard Error	3.48
Observations	65

Table 63: Regression analysis results for height vs RULA score.

Regression Statistics Height vs RULA	
Multiple R	0.1
R Square	0.02
Adjusted R Square	0.00
Standard Error	3.53
Observations	65

Table 64: Regression analysis results for height vs HumanTech score.

Regression Statistics Height vs HumanTech	
Multiple R	0.15
R Square	0.02
Adjusted R Square	0.00
Standard Error	3.53
Observations	65

Research Question 1

Finally, the primary research question can be addressed: “Is virtual reality a feasible substitute for physical ergonomic assessment?” The initial prediction associated with this research question was yes from a fluid data capture standpoint, and while there is some validity to that concept, it does not tell the whole story. Table 65 displays a percentage of equivalence based on each assessment tool. As shown, HumanTech provided the most viable method with 100% equivalence (due to the analysis being a single continuous assessment value). This was followed by RULA, Dtrack, and REBA which were all within 12% of one another. Being similarly formatted assessments (stationary moments in time), this was to be expected. Finally, Delsys had nearly no correlation in values. This was likely a result of this study's design falling victim to its own circumstance. The difficult part interactions have been noted. Those variances alone, coupled with the different muscles utilized for grip functions in the VR controllers, unfortunately deemed EMG data as non-suitable assessment tool for virtual digital twins.

Table 65: Percentage of equivalence based on each assessment tool.

Analysis Tool	Analyses Deemed Equivalent	Total Data Points	% Equivalent
REBA	3	8	38%
RULA	4	8	50%
HumanTech	1	1	100%
Delsys	1	140	1%
Dtrack	7	16	44%

Cycle Times

Overall Cycle Times

Table 66 displays a breakdown/key of the 14-step PEAT assembly process. Additionally, a cycle time breakdown between each assembly step in both environments has also been generated. Figure 62 displays the cumulative average cycle time for each assembly step across all participants. In both environments, installation of the 4 cover bolts had the highest cycle time. From a virtual reality standpoint, these high cycle times are followed by installation of the lifting bracket bolts, and the swivel knob. Many factors contributed to higher VR cycle times, but the largest influence was likely the manipulation of the smaller interactive parts. Many participants struggled with both the swivel knob rotation and the cover bolt installations. The small parts were difficult to interact with. While the small pointer balls programmed at the end of each controller provided some guidance, it took a significant amount of time for threaded component installations. Participants had to slightly exaggerate movements for the system to correctly pick up the interaction. This is believed to be an unfortunate shortcoming related to the VRTK package utilized for the assembly snap to fit function in unity. These results were anticipated based on the circumstance and nature of this environment. Additionally, anecdotally, researchers noted that participants reported having to squeeze the right controller a bit harder than the left to pick up the grip signal. For this reason, many participants, regardless of their indicated handedness, opted to utilize the left controller.

Table 66: PEAT assembly step breakdown/description

Step	Assembly Description
1	Pick and place housing on assembly fixture
2	Rotate swivel knob
3	Lift up hatch
4	Pick and install slider block
5	Replace hatch
6	Rotate swivel knob back into place
7	Pick and install cover plate
8	Pick, install, and torque 4 cover plate bolts
9	Pick and install the lifting bracket
10	Pick and install the two lifting bracket bolts
11	Rotate the fixture 90 degrees to the left
12	Pick and install card
13	Rotate the fixture 90 degrees to the left
14	Pick and install the threaded shaft

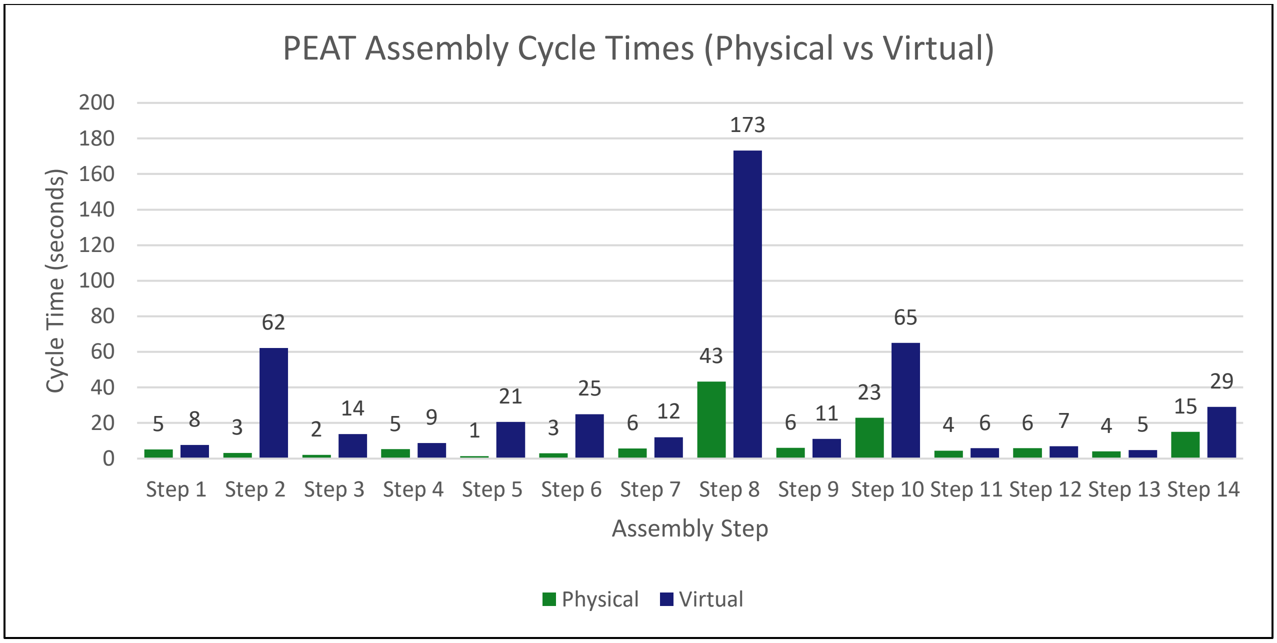


Figure 62: PEAT assembly cycle time breakdown by assembly step and environment

Figure 63 displays the average cycle times by environment across all participants. On average, the virtual assembly took 5.31 additional minutes than the physical assembly.

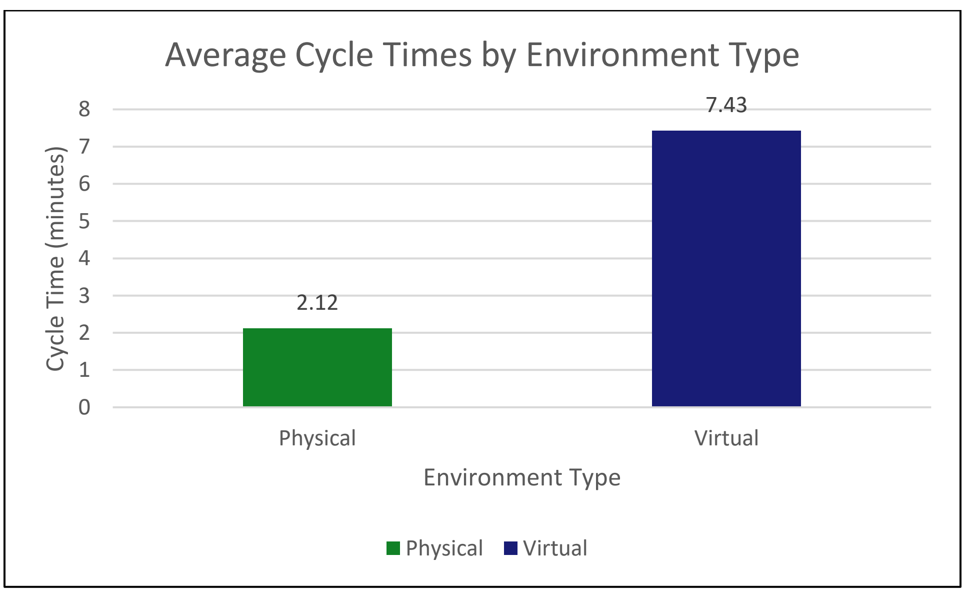


Figure 63: Average cycle times by environment (minutes)

Figure 64 displays box plots for the total cumulative cycle time data for each environment in seconds.

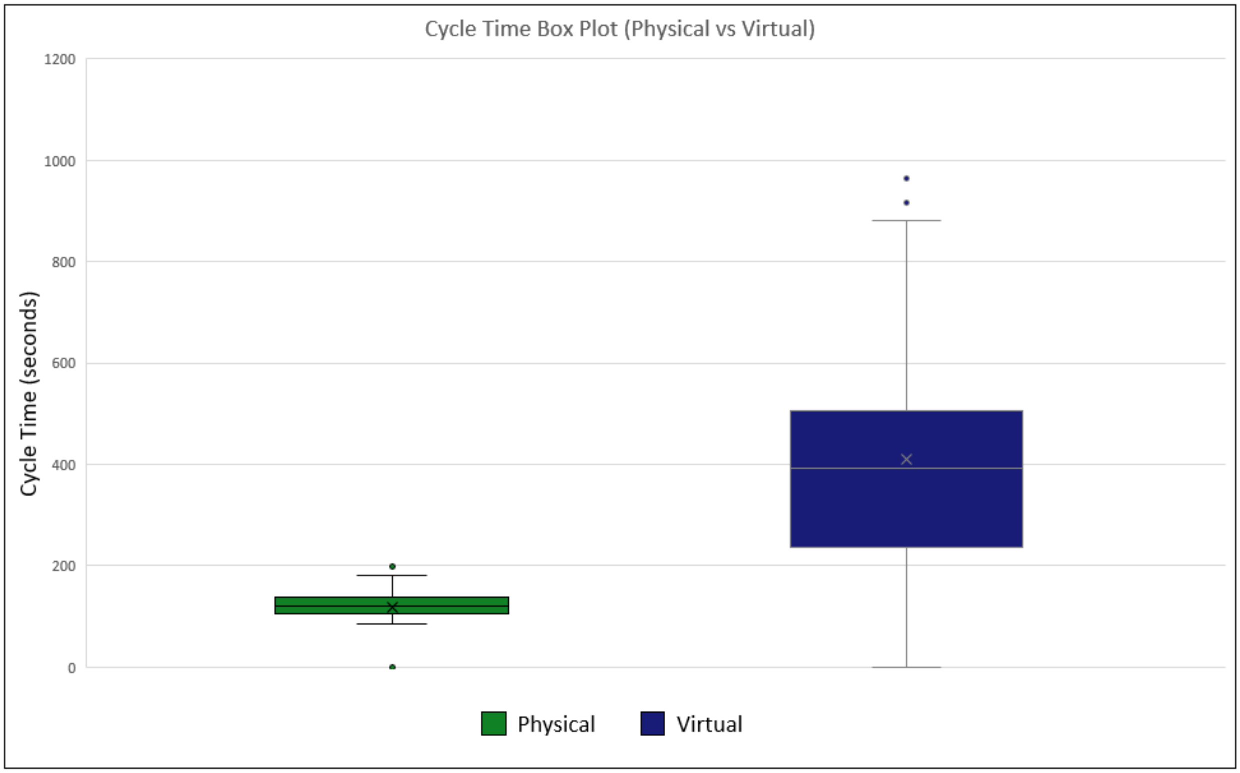


Figure 64: Cycle time box plot data for total cumulative assembly in each environment (seconds)

Additionally, Figure 65 displays the cycle time box plots broken out by assembly step in both environments.

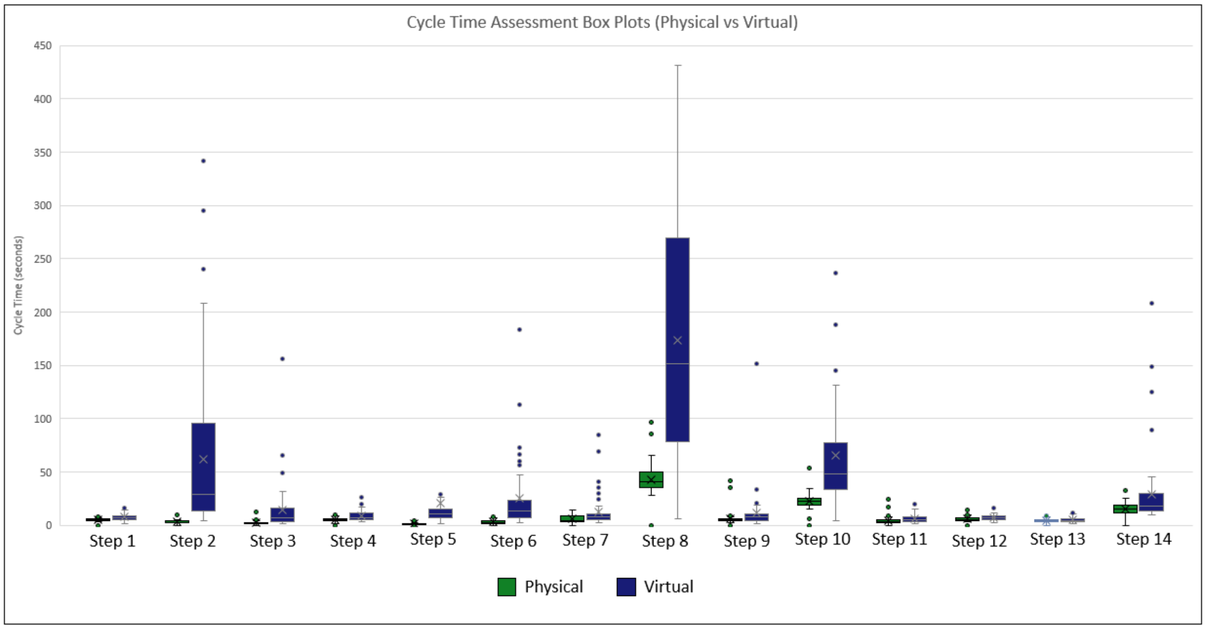


Figure 65: Cycle time assessment box plot (physical and virtual environments)

Summary statistics for both the physical and virtual trials are displayed in Table 67. It is important to note that these statistics are in seconds. The average standard deviation for the physical assembly was about 38 seconds, while the standard deviation for the virtual cycle time was about 3 and a half minutes.

Table 67: Cycle time summary statistics

Statistic	Physical	Virtual
Mean	117.8	409.2
Standard Deviation	38.14	211.3
Standard Mean Error	4.73	26.21
Upper 95% Mean	127.23	461.59
Lower 95% Mean	108.36	356.88

Counter-Balancing Analysis

As stated previously, counterbalancing was utilized in this study to reduce order effects. As displayed in Figure 66, less than 10 seconds of difference was observed between cycle times between those who performed physical first vs. virtual first. This indicates that participants performed within 58 seconds maximum of one another, regardless of which environment they were exposed to first. The average cycle time in the physical environment was 99 seconds (~1.65 minutes) with a standard deviation of 57 seconds (~1 minute) while the virtual environment had an average cycle time of 346 seconds (~6 minutes) with a standard deviation of 240 seconds (~4 minutes).

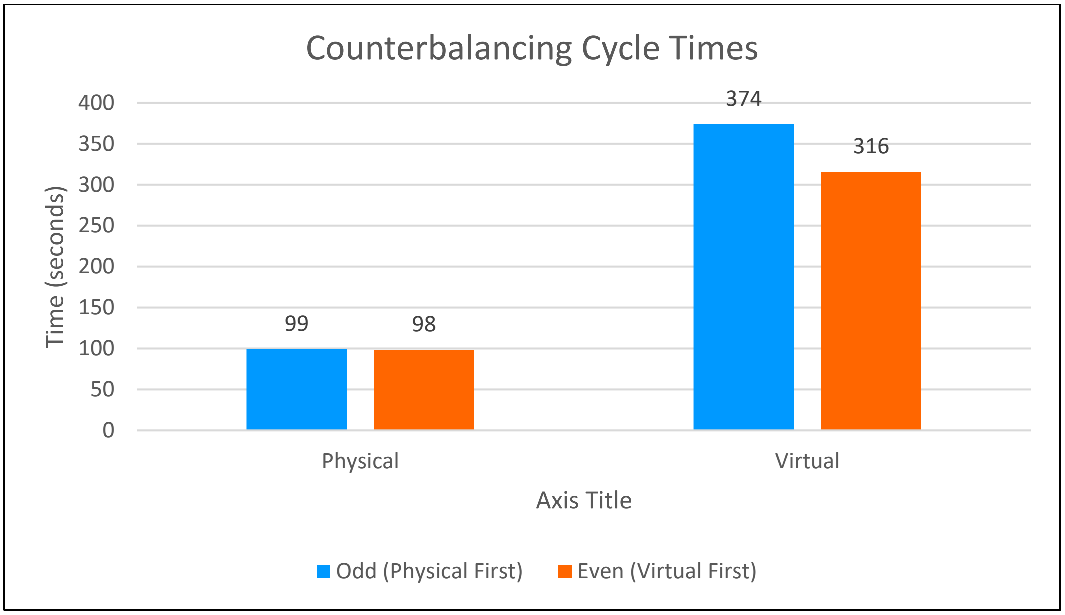


Figure 66: Counterbalanced cycle times

General Survey Summaries

Mental Rotation Test

The average score of the mental rotation test was 35 points out of a possible 40 (2 points per question). A total of 10 participants did get a perfect 40/40. Figure 67 displays the resultant box plot form the mental rotation test results.

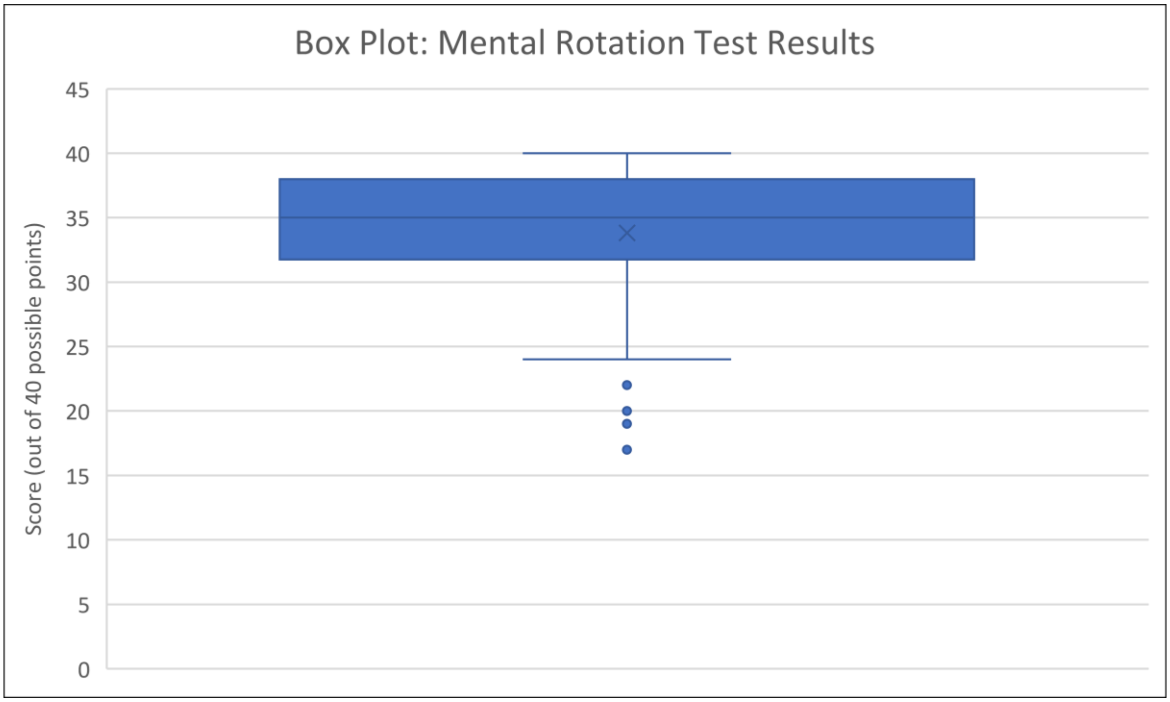


Figure 67: Box plot of mental rotation test results.

Pre-Study Survey

Below are a few additional results from the pre-study survey that were not analyzed in the research questions above.

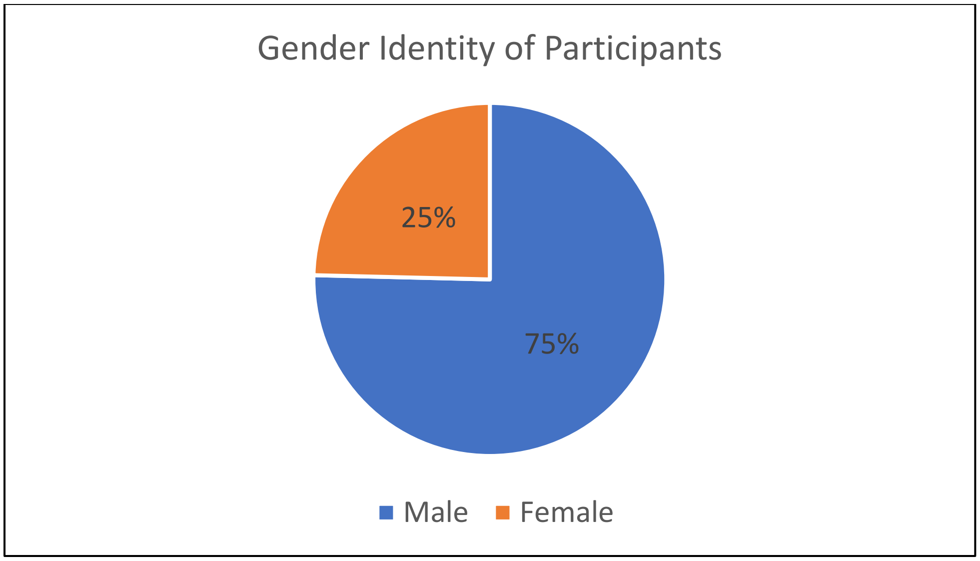


Figure 68: Reported gender identity of participants.

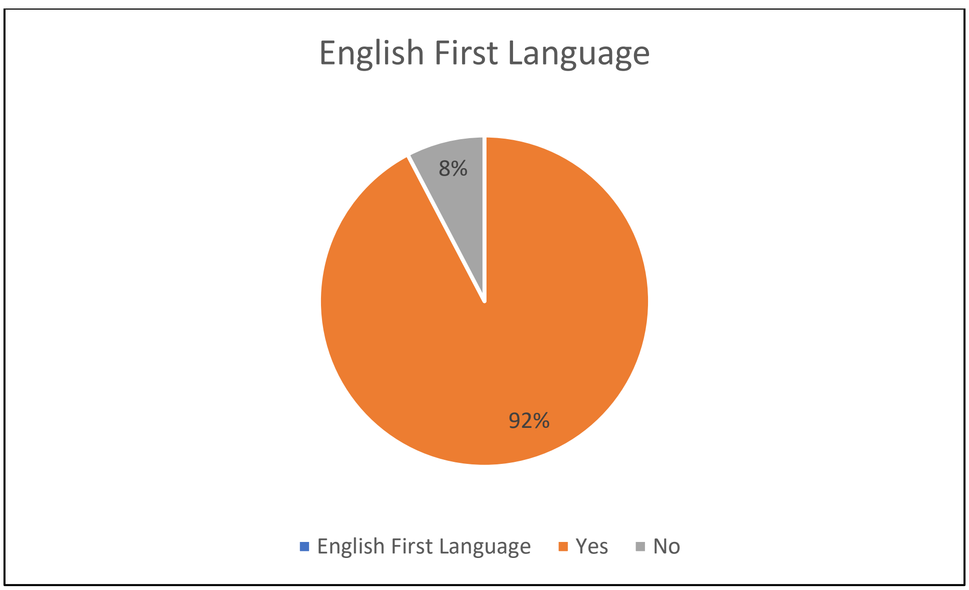


Figure 69: Participant response percentage to “Is English your first language?”

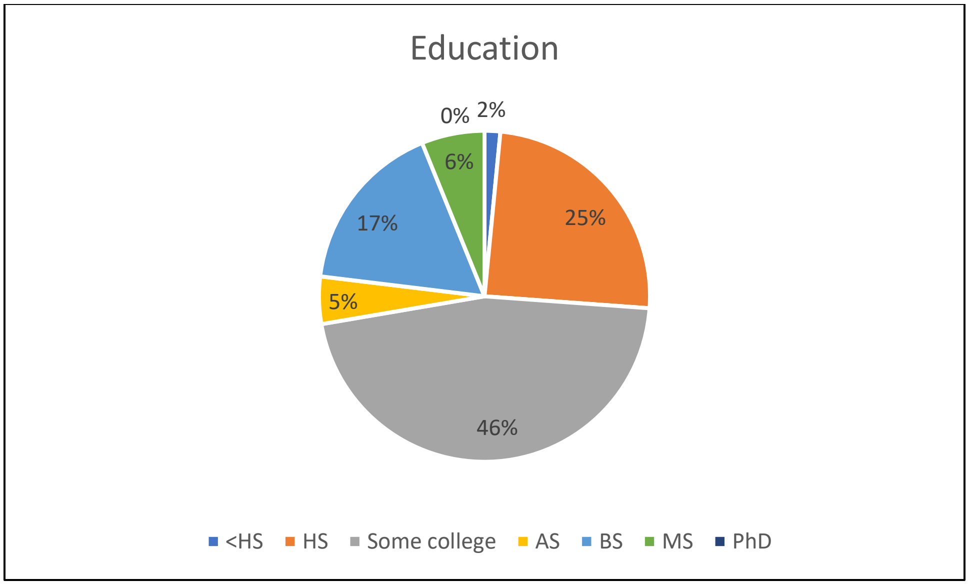


Figure 70: Participants reported highest level of education achieved.

Post-Study Survey

The post-study survey consisted of three primary questions, with a 4th allowing the opportunity to provide additional feedback. This survey was to primarily provide feedback to the research team regarding the overall quality of the digital twin replica as well as the training material. Their corresponding figures (Figure 71 through Figure 73) display the results of these three questions. There was a 100% response rate associated with these questions.

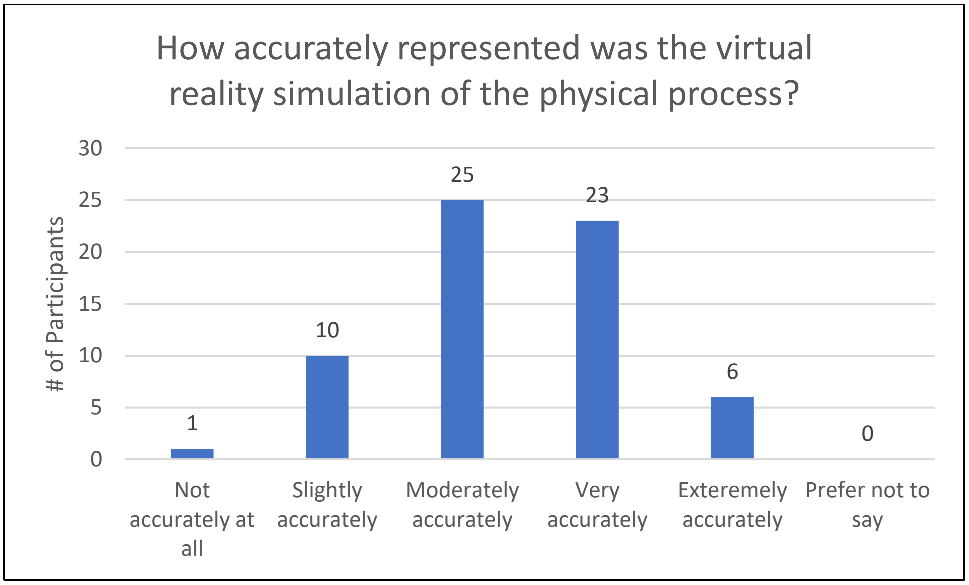


Figure 71: Graphical representation of participant feedback results regarding virtual reality simulation accuracy

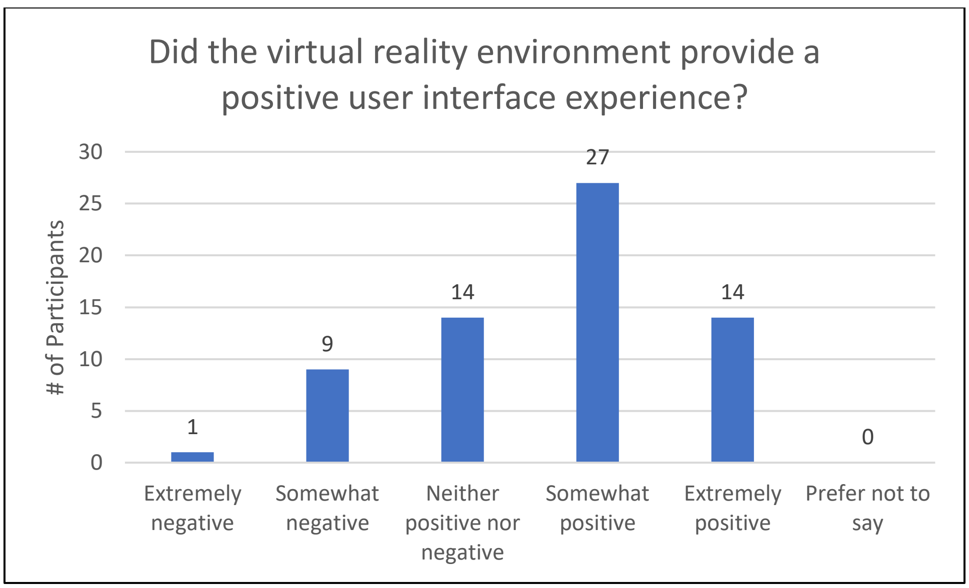


Figure 72: Graphical representation of participant feedback results regarding virtual reality user experience

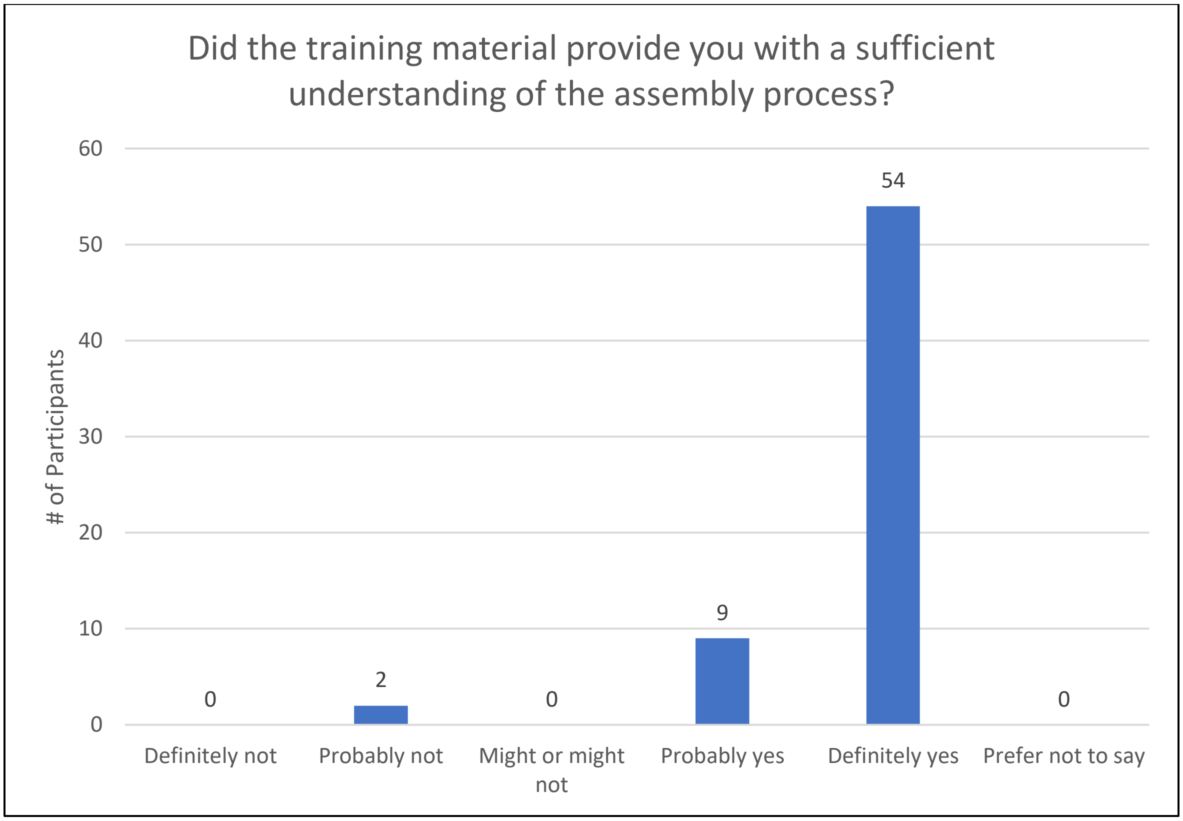


Figure 73: Graphical representation of participant feedback results regarding training material sufficiency

CHAPTER 5. DISCUSSION & CONCLUSIONS

This study provided insight to different ergonomic assessment tools and their ability to couple with virtual reality technology. Taking a multiple system assessment approach allowed for the exploration of various assessment tools. An environment was developed to encompass common manufacturing movements applicable in a variety of different industries, in hopes to support justification for use of virtual reality in ergonomic assessment across multiple manufacturing domains, as most research around this topic has previously focused on the automotive industry.

Contribution

This study established that circumstantially, virtual reality can replace physical ergonomic analysis in certain postures for general analysis, especially farther or higher upper body reaches. As technology continues to develop, it is likely that more postures will be able to be simulated accurately in VR. Utilizing a continuous data capture software proved that virtual reality is a feasible substitute for physical ergonomic assessment. Positional analysis does have a number of limitations both in the physical and virtual environment. This study identified a few of them.

Additionally, this study took the opportunity to utilize multiple tracking systems via simultaneous data capture. This provided the unique opportunity to track the same movements with different measurement systems and discern the advantages and disadvantages of each in VR.

The ability to perform ergonomic assessments in virtual reality provides a large opportunity in terms of return on investment for companies. Not only would this allow for remote assessment and multi-location collaboration, but also improve new process/assembly integration standpoint. Having the ability to understand ergonomic risk associated with a new assembly environment prior to physical development of a workstation and product prototype allows for design modification early on in the process, saving a notable amount of time, resources, and rework.

Limitations

As stated above, the study reveals some unique caveats that need to be considered. For example, the programming in the virtual environment made small part interactions and assembly very difficult. This concept, coupled with the use of controllers instead of virtual reality compatible tracking gloves, made it difficult for smaller movements to be performed with high fidelity in the virtual environment. Additionally, the right controller periodically demonstrated periodic buggy behavior (this was later deduced to be a programming latency issue as opposed to an actual hardware issue), and participants simply opted to use the other hand instead, regardless of handedness.

Another unfortunate circumstance was the lack of access to the software allowing for fluid data capture of the Dtrack system. With greater funding and the ability to implement this capability, it is predicted that the results would have shown more equivalence, due to a greater number of frames from the continuous data stream.

While the above limitations are circumstantial to the nature of this study, other limitations may transfer more generally across other related studies. For example, EMG data would likely prove to be an invalid measurement tool in virtual reality in general simply due to the nature of the data and immersive environment. For example, participants were observed to have more head movement in virtual reality than in the physical environment. This observation was corroborated in the results provided from sensors 9 and 10 (left and right sides of the neck) in the Delsys system. This concept would likely carry over to another study due to the natural response/performance in a virtual environment.

Future Work

Future research should be performed to accommodate the growing and everchanging technology development. As new ergonomic and immersive technologies develop, research should continue to investigate the coupling multiple technologies. As this study indicated, results are more repeatable with continuous data capture in ergonomic specific software. Utilizing a more cable software such as Xsens or Noraxon could provide a well-rounded assessment.

Future research should also investigate new technologies to fill the gaps identified in this study. For example, virtual reality tracking gloves allow for capture of dexterity in hand/component interaction. A detailed study focusing on producing repeatable metrics from the EMG data could be feasible with the right technology pairing.

Another opportunity made possible by this research is the potential to combine tracking systems. While Dtrack and Delsys are not ergonomic-specific evaluation tools, the coupling of the two could provide unique insight. Delsys' EMG/IMU capability allows for the tracking of force. This data coupled with the continuous capture of positional data could allow for accurate and unique analysis data from a positional force/strain on each muscle standpoint. Future work should take advantage of this unique opportunity.

Finally, there are many different types of virtual reality applications as well as different display technologies. From HMDs to CAVE-style VR experiences, it is important to explore what each of these systems could contribute to ergonomic analysis.

REFERENCES

[1] A. A. Neto, F. Deschamps, E. R. Da Silva, and E. P. De Lima, "Digital twins in manufacturing: An assessment of drivers, enablers and barriers to implementation," in *Procedia CIRP*, Elsevier B.V., 2020, pp. 210–215. doi: 10.1016/j.procir.2020.04.131.

[2] Ma, Dengzhe., Gausemeier, Jürgen., Fan, Xiumin., & Grafe, Michael. (2011). *Virtual Reality & Augmented Reality in Industry edited by Dengzhe Ma, Jürgen Gausemeier, Xiumin Fan, Michael Grafe.* (D. Ma, J. Gausemeier, X. Fan, & M. Grafe, Eds.; 1st ed. 2011..)

[3] S. Lim and C. D'Souza, "A narrative review on contemporary and emerging uses of inertial sensing in occupational ergonomics," *Int J Ind Ergon*, Mar. 2020.

[4] Hignett, S., & Ergonomist, L. M. (2000). Rapid Entire Body Assessment (REBA). In *Applied Ergonomics* (Vol. 31).

[5] Mcatamney, L., & Corlett, E. N. (1993). RULA: a survey method for the investigation of work-related upper limb disorders. In *Applied Ergonomics* (Vol. 24, Issue 2).

[6] Xsens. (2023). *Xsens Movella Website*. Movella Inc. https://www.movella.com/products/xsens

[7] Noraxon. (2022). *Noraxon Website*. https://www.noraxon.com/

[8] VelocityEHS. (n.d.). VelocityEHS_Solution_Sheet_Industrial_Ergonomics. *2022*.

[9] J. Dul and B. Weerdmeester, *Ergonomics for Beginners A Quick Reference Guide*, Third Edition. Boca Raton: CRC Press Taylor & Francis Group, 2008.

[10] "Safety and Health Movement, Then and Now," pp. 1–17. Accessed: Apr. 05, 2023. [Online]. Available: https://www.pearsonhighered.com/assets/samplechapter/0/1/3/4/0134678710.pdf

[11] C. Vivian Madueke and I. Chimezie Emerole, "Saudi Journal of Business and Management Studies Organizational Culture and Employee Retention of Selected Commercial Banks in Anambra State", doi: 10.21276/sjbms.2017.2.3.16.

[12] A. G. Da Silva, I. Winkler, M. M. Gomes, and U. D. M. P. Junior, "Ergonomic Analysis supported by Virtual Reality: A Systematic Literature Review," in *Proceedings - 2020 22nd Symposium on Virtual and Augmented Reality, SVR 2020*, Institute of Electrical and Electronics Engineers Inc., Nov. 2020, pp. 463–468. doi: 10.1109/SVR51698.2020.00074.

[13] National Safety Council, "Work Injury Costs," *NSC*, 2023.

[14] U.S. Bureau of Labor Statistics, "Injuries, Illnesses, and Fatalities ," 2022.

[15] D. V. Dorozhkin, J. M. Vance, G. D. Rehn, and M. Lemessi, “Coupling of interactive manufacturing operations simulation and immersive virtual reality,” *Virtual Real*, vol. 16, no. 1, pp. 15–23, Mar. 2012, doi: 10.1007/s10055-010-0165-7.

[16] M. Vega-Barbas, J. A. Diaz-Olivares, K. Lu, M. Forsman, F. Seoane, and F. Abtahi, “P-ergonomics platform: Toward precise, pervasive, and personalized ergonomics using wearable sensors and edge computing,” *Sensors (Switzerland)*, vol. 19, no. 5, Mar. 2019, doi: 10.3390/s19051225.

[17] M. Peruzzini, F. Grandi, S. Cavallaro, and M. Pellicciari, “Using virtual manufacturing to design human-centric factories: an industrial case,” *International journal of advanced manufacturing technology*, vol. 115, no. 3, pp. 873–887, 2021, doi: 10.1007/s00170-020-06229-2.

[18] F. Caputo, A. Greco, E. D’Amato, I. Notaro, and S. Spada, “On the use of Virtual Reality for a human-centered workplace design,” in *Procedia Structural Integrity*, Elsevier B.V., 2018, pp. 297–308. doi: 10.1016/j.prostr.2017.12.031.

[19] L. E. Whitman, M. Jorgensen, K. Hathiyari, and D. Malzahn, “Virtual reality: Its usefulness for ergonomic analysis,” in *Proceedings - Winter Simulation Conference*, 2004, pp. 1740–1745. doi: 10.1109/wsc.2004.1371525.

[20] U.S. Bureau of Labor Statistics, “32% oof Nonfatal Injuries Resulting in Days Away from Work Treated in Emergency Room in 2019,” *U.S. Bureau of Labor Statistics*, Aug. 16, 2021. https://www.bls.gov/opub/ted/2021/32-percent-of-nonfatal-injuries-resulting-in-days-away-from-work-treated-in-emergency-room-in-2019.htm (accessed Apr. 06, 2023).

[21] Wo Mexico Asia Europ, anding. (n.d.). *Design Guidelines for Ergonomics Hand working heigh*. Retrieved March 5, 2023, from https://ths.humantech.com/danfoss/ind/edg

[22] Steam. (2023, January 1). *Valve Index Software*. https://www.valvesoftware.com/en/index/headset

[23] A. Hedge, “Ergonomics Plus REBA Employee Assessment Worksheet”, Accessed: Mar. 05, 2023. [Online]. Available: https://ergo-plus.com/wp-content/uploads/REBA.pdf

[24] A. Hedge, “Ergonomics PLus RULA Employee Assessment Worksheet”, Accessed: Mar. 05, 2023. [Online]. Available: https://ergo-plus.com/wp-content/uploads/RULA.pdf

[25] “Trigno ® Wireless Biofeedback System User’s Guide,” 2021.

[26] Minitab LLC, “Enter your data for Power and Sample Size for Equivalence Test with Paired Data,” 2021.

[27] R. B. Ekstrom, J. W. French, and H. H. Harman, “Manual for the Kit of Factor-Referenced Cognitive Tests (1976),” 1976.

[28] D. Lakens, A. M. Scheel, and P. M. Isager, “Equivalence Testing for Psychological Research: A Tutorial,” *Adv Methods Pract Psychol Sci*, vol. 1, no. 2, pp. 259–269, Jun. 2018, doi: 10.1177/2515245918770963.

[29] P. M. Dixon, P. F. Saint-Maurice, Y. Kim, P. Hibbing, Y. Bai, and G. J. Welk, “A Primer on the Use of Equivalence Testing for Evaluating Measurement Agreement,” *Med Sci Sports Exerc*, vol. 50, no. 4, pp. 837–845, Apr. 2018, doi: 10.1249/MSS.0000000000001481.

[30] L. Minitab, “Minitab,” *Minitab, LLC*, 2023. https://www.minitab.com/en-us/ (accessed Mar. 12, 2023).

[31] Keith Calkins, “Correlation Coefficients,” *Andrews University*, Jul. 18, 2005.

APPENDIX A: IRB APPROVAL LETTER

IOWA STATE UNIVERSITY
OF SCIENCE AND TECHNOLOGY

Institutional Review Board
Office of Research Ethics
Vice President for Research
2420 Lincoln Way, Suite 202
Ames, Iowa 50014
515 294-4566

Date: 10/27/2022

To: Kathryn Lieffrig   Stephen Gilbert

From: Office of Research Ethics

Title: Feasibility of using VR to perform Ergonomic Assessment (PEAT)

IRB ID: 22-212

Submission Type: Modification   **Review Type**: Expedited

Approval Date: 10/27/2022   **Approval Expiration Date:** N/A

The project referenced above has received approval from the Institutional Review Board (IRB) at Iowa State University according to the dates shown above. Please refer to the IRB ID number shown above in all correspondence regarding this study.

To ensure compliance with federal regulations (45 CFR 46 & 21 CFR 56), please be sure to:

- **Use only the approved study materials** in your research, including the **recruitment materials and informed consent documents that have the IRB approval stamp**.
- **Retain signed informed consent documents for 3 years after the close of the study,** when documented consent is required**.**
- **Obtain IRB approval prior to implementing any changes** to the study or study materials.
- **Promptly inform the IRB of any addition of or change in federal funding for this study.** Approval of the protocol referenced above applies only to funding sources that are specifically identified in the corresponding IRB application.
- **Inform the IRB if the Principal Investigator and/or Supervising Investigator end their role or involvement with the project** with sufficient time to allow an alternate PI/Supervising Investigator to assume oversight responsibility. Projects must have an eligible PI to remain open.
- **Immediately inform the IRB of** (1) **all serious and/or unexpected** adverse experiences involving risks to subjects or others; and (2) **any other** unanticipated problems **involving risks** to subjects or others.
- IRB approval means that you have met the requirements of federal regulations and ISU policies governing human subjects research. **Approval from other entities may also be needed.** For example, access to data from private records (e.g., student, medical, or employment records, etc.) that are protected by FERPA, HIPAA, or other confidentiality policies requires permission from the holders of

those records. Similarly, for research conducted in institutions other than ISU (e.g., schools, other colleges or universities, medical facilities, companies, etc.), investigators must obtain permission from the institution(s) as required by their policies. **IRB approval in no way implies or guarantees that permission from these other entities will be granted.**

- Your research study may be subject to **post-approval monitoring by Iowa State University's Office of Research Ethics**. In some cases, it may also be subject to formal audit or inspection by federal agencies and study sponsors.

- Upon completion of the project, transfer of IRB oversight to another IRB, or departure of the PI and/or Supervising Investigator, please initiate a Project Closure to officially close the project. For information on instances when a study may be closed, please refer to the IRB Study Closure Policy.

If your study requires continuing review, indicated by a specific Approval Expiration Date above, you should:

- **Stop all human subjects research activity if IRB approval lapses**, unless continuation is necessary to prevent harm to research participants. Human subjects research activity can resume once IRB approval is re-established.

- **Submit an application for Continuing Review** at least three to four weeks prior to the **Approval Expiration Date** as noted above to provide sufficient time for the IRB to review and approve continuation of the study. We will send a courtesy reminder as this date approaches.

Please don't hesitate to contact us if you have questions or concerns at 515-294-4566 or IRB@iastate.edu.

APPENDIX B: SURVEYS

Pre-Study Survey

1. What is your gender?
    a) Male
    b) Female
    c) Non-binary/ Gender Non-conforming
    d) Prefer not to say
    e) Other/Not Listed
2. What is your age?
    a) 18-21
    b) 22-24
    c) 25-34
    d) 35-44
    e) 45-54
    f) 55-64
    g) 65-74
    h) 75-84
    i) 85 or older
    j) Prefer not to answer
3. Are you right or left-handed?
    a) Right
    b) Left
    c) Ambidextrous
    d) Prefer not to say
4. Is English your 1st language?
    a) Yes
    b) No
    c) Prefer not to say

4B. (If "No" is selected for Question 4) Please select your first language
    a) Chinese
    b) Spanish
    c) Hindi
    d) Bengali
    e) Portuguese
    f) Russian
    g) Japanese
    h) Turkish
    i) Korean
    j) French
    k) German
    l) Vietnamese
    m) Polish
    n) Other
    o) Prefer not to say

5. What is the highest degree or level of school you have completed?
    a) Less than a high school diploma
    b) High school degree or equivalent (e.g. GED)
    c) Some college, no degree
    d) Associate degree (e.g. AA, AS)
    e) Bachelor’s degree (e.g. BA, BS)
    f) Master’s degree (e.g. MA, MS, MEd)
    g) Doctorate or professional degree (e.g. MD, DDS, PhD)
    h) Prefer not to answer
6. How many days on average/week are you physically active?
    a) 0 days/week
    b) 1-3 days/week
    c) 4-6 days/week
    d) 7 days/week
    e) Prefer not to answer
7. Do you do any of these exercises on a regular basis?
    a) Ride a bicycle
    b) Jog/walk
    c) Lift weights
    d) Play a sport
    e) Other
    f) None
    g) Prefer not to answer
8. Compared to other people your age, would you say you are physically more active, less active, or about as active?
    a) More active
    b) Less active
    c) About as active
    d) Prefer not to answer

8B. (If more/less active selected) is that (a lot more or a little more active/ a lot or a little less active)?

    e) Lot more
    f) Little more
    g) Lot less
    h) Little less
    i) Prefer not to answer
9. What is your weight?
    a) *Text field*
    b) Prefer not to say
10. What is your height
    a) *Feet field*
    b) *Inches Field*
11. Have you had any exposure to virtual reality?
    a) No exposure
    b) Some exposure

c) Regular exposure
d) Extensive exposure
e) Prefer not to say

12. Please describe the capacity at which you had exposure to virtual reality if any. (Ex. I have used an Oculus headset for a game, I develop simulations, etc.)
    a) *Text field*
13. Please describe the capacity at which you had exposure to 3D modeling software if any (Ex. I have used it in one class, I use it regularly in my curriculum, I use it periodically in the workplace, etc.)
    a) *Text field*
14. Have you had any exposure to a manufacturing/assembly environment? If yes, please provide duration and details of work. E.g. 3 months as an intern, 3 years as an operator, etc.
    a) *Text field*
15. If you have any additional information about your experience assembling things that you think would be useful, please feel free to write it below.
    a) “Text field*

Physical Survey

1. How difficult was it to assemble the product?
    b) Extremely difficult
    c) Somewhat difficult
    d) Neither easy nor difficult
    e) Somewhat easy
    f) Extremely easy
    g) Prefer not to say
2. Did you experience any ergonomic (comfortable/safe working conditions) discomfort?
    a) Yes
    b) No
3. If yes, please explain what you experienced
    a) *Text field*

Virtual Survey

1. How difficult was it to assemble the product?
    a) Extremely difficult
    b) Somewhat difficult
    c) Neither easy nor difficult
    d) Somewhat easy
    e) Extremely easy
    f) Prefer not to say
2. Did you experience any cybersickness discomfort?
    a) Yes
    b) No
    c) Prefer not to say

3. If yes, please explain what you experienced
    a) *Text field*
4. Did you experience any ergonomic (comfortable/safe working conditions) discomfort?
    a) Yes
    b) No
    c) Prefer not to say
5. If yes, please explain what you experienced.
    a) *Text field*

Post Study Survey

1. How accurately represented was the virtual reality simulation of the physical process?
    a) Not accurately at all
    b) Slightly accurately
    c) Moderately accurately
    d) Very accurately
    e) Extremely accurately
    f) Prefer not to say
2. Did the virtual reality environment provide a positive user interface experience?
    a) Extremely negative
    b) Somewhat negative
    c) Neither positive nor negative
    d) Somewhat positive
    e) Extremely positive
    f) Prefer not to say
3. Did the training material provide you with a sufficient understanding of the assembly process?
    a) Definitely not
    b) Probably not
    c) Might or might not
    d) Probably yes
    e) Definitely yes
    f) Prefer not to say
4. Is there any additional feedback you would like to provide?
    a) *Text field*

APPENDIX C: PARTICIPANT RUN SHEET

Participant Run Sheet

Note: Blue text was verbally read to each participant while black text was indicative of physical actions.

Introduction:

Good Morning/Afternoon! My name is _______ and welcome to the PEAT study! The study you are about to participate in is attempting to justify the ability to utilize virtual reality to perform ergonomic (or comfortable/safe working conditions) assessments. In this experiment, you will be asked to assemble PEAT 3 separate times. The first time will just be a trial run so you can get to know the product/process. You will then assemble PEAT twice more with all of our motion tracking systems; once in a physical environment, and once in a virtual environment.

Pre Study Survey:

You will begin by taking a pre-study survey. This is simply to gain a bit of information regarding your exposure to different situations for future data analysis. This information is de-identified and will not be tied to you in any way. You may now begin the pre-study survey.

Mental Rotation Test:

You will now take a mental rotation test. This is a test of your ability to look at a drawing of a given object and find the same object within a set of dissimilar objects. The only difference between the original object and the chosen object will be that they are presented at different angles. For each problem, there is a primary object on the far left. You are to determine which two of the four objects to the right are the same object shown on the far left. Your score will reflect both correct and incorrect responses so you should not guess unless you have some idea which choice is correct. You may now begin the mental rotation test.

Training:

Verbal overview/description of PEAT

This is PEAT! PEAT is an acronym that stands for “Portable Ergonomic Assessment Tool”. PEAT is a simple 3D printed box, onto which 11 parts will be assembled. PEAT was designed to incorporate common manufacturing movements, as our research is industry based.

- During assembly, the main base of PEAT (the box component), will be placed on an assembly fixture. This fixture will be used to rotate the part, via grabbing the gold pin and spinning as needed
- Do you have any questions?

- Show training video and present standard work instructions

We will now play a training video to familiarize you with the PEAT assembly process. I will also give you the standard work instructions that you can also reference.

- Training wrap up

  You are now ready to begin your first assembly! Again, we will be recording this session, but this is just a trial run for you to get comfortable with the product. Do you have any questions before we get started?
- NOTE: cap this portion of the study at 10 minutes

Trial 1 (Educational Run):

- A copy of the standard work has been provided for reference. Please stand in a neutral position before I say "Go"
- Begin video recording (Again this is just for a cycle time for us) Following this, disassemble PEAT and restock bench for actual experiment run.
- Go ahead and try assembling and let me know if you have any questions!

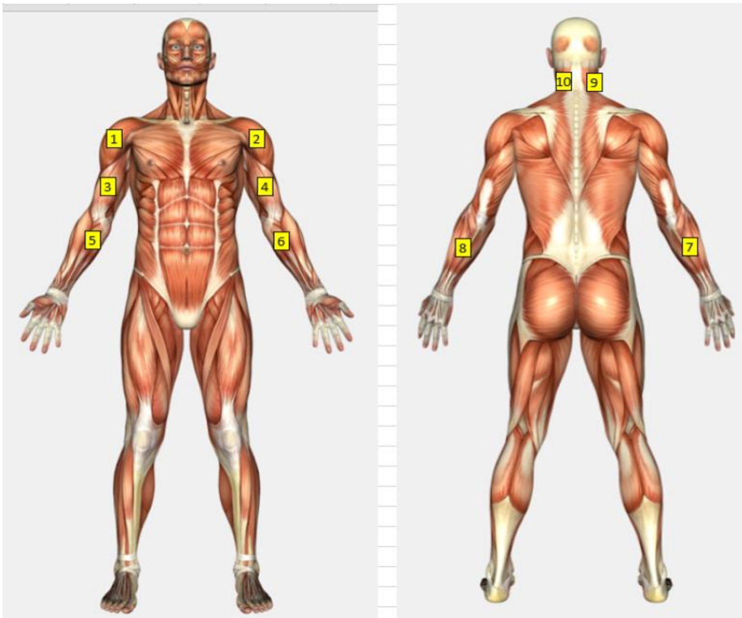
Experiment Trial Setup:

- We will now introduce the participant to the actual study at this point and hook up all sensors/recording devices.

We will now place 2 types of trackers on your body. The first is a wireless system that tracks your muscle activation. These sensors will be applied directly to your skin with medical grade double sided sticky tape, and medical grade bandages to ensure they don't fall off during assembly. It was included in the consent form, but I want to make sure you do not have any sensitives to medical grade tape? (If so, ask to leave study). The second is a camera-based motion tracker ball system, which will be applied with Velcro straps.

We do have a 3rd tracking system that is a camera recording based software which does a skeletal video overlay. Again, your face will be blocked off per the consent form, and the raw footage will be deleted.

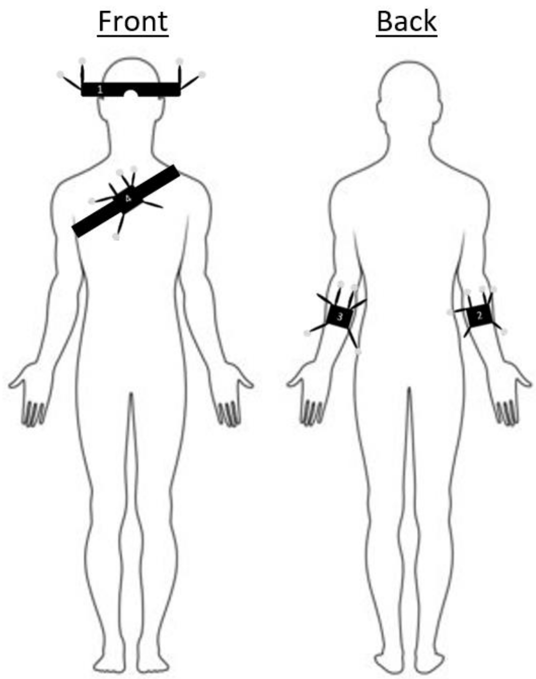
Apply Delsys Sensors



Sensor #	Muscle Name	Description
1	R DELTOID	Right Shoulder
2	L DELTOID	Left Shoulder
3	R BICEPS BRACHI	Right Upper Inner Arm
4	L BICEPS PRACHI	Left Upper Inner Arm
5	R FLEXOR CARPI RADIALIS	Right Lower Inner Arm
6	L FLEXOR CARPI RADIALIS	Left Lower Inner Arm
7	R EXTENSOR DIGITORUM	Right Lower Outer Arm
8	L EXTENSOR DIGITORUM	Left Lower Outer Arm
9	R TRAPEZIUS UPPER FIBERS	Right Back of Neck
10	L TRAPEZIUS UPPER FIBERS	Left Back of Neck

Apply ART Sensors

Sensor #	Location
1	Glasses
2	Right Arm
3	Left Arm
4	Sternum



Physical Assembly:

- If the participant has an odd participant number, run the physical assembly sequence first. (NOTE: don't forget to swap the ART glasses/head tracker!)

We will now begin the physical assembly trial. Do you have any questions? I will now start all of the recording software for the sensor tracking. You may begin the assembly when I say "Go"

- Begin Dtrack recording
- Begin Delsys recording
- Begin HumanTech recording
- Open Camera on PC and place VR headset on PC box

GO!

<u>AFTER TRIAL</u>

Stop Recordings:

- Delsys
  - Save Delsys to the correct spot (refer to Delsys Standard Work Doc)
- OBS
- Camera Recording

We will now have you complete a short physical assembly survey about your experience.

- Begin the physical assembly survey for the participant

Virtual Assembly:

- If the participant has an even participant number, run the virtual assembly sequence first. (NOTE: don't forget to swap the ART glasses/head tracker!)

We will now begin the virtual assembly trial. I will now place you in a virtual reality headset to assemble the virtual version of PEAT. You will first be placed in a practice environment to allow yourself to familiarize yourself with the controls and how to navigate the virtual space. You will then be placed in the PEAT environment. I will now place the virtual reality headset on you and we will adjust it so its comfortable and focused. Do you have any questions?

- Place headset on participant. Note the IPD roller on the bottom of the headset (indicate this is for focus to center on their eyes). The strap on top can be used to allow the headset to sit higher or lower (this can also help with focus). The dial on the back of the headset tightens it.
- Place participant in training environment

Welcome to the training environment. You will see a workbench in front of you with 3 shapes to be placed into the table. To pick up objects, simply squeeze the controller with your hand on the object (no button pushes are necessary). Please note that the cylinder component is in fact threaded and must be turned down into the table. Begin by placing it in its respective location as it will snap into place. Then grab and turn it, as though you were turning down a large bolt. Do you have any questions?

- Prepare your stopwatch to take a cycle time.

You may now begin! Please let me know when you feel comfortable with the training environment.

- Push start on the stopwatch.
- Once the participant has completed one round of the trial assembly, stop the timer.
- Make note of the cycle time in the cycle time spreadsheet (or on a piece of paper and transfer the information after the participant has left)

We will now begin the virtual assembly trial. I will now start all of the recording software for the sensor tracking. You may begin the assembly when I say "Go"

- Begin Dtrack recording
- Begin Delsys recording
- Begin HumanTech recording

GO!

<u>AFTER TRIAL:</u>

Stop recording

- Delsys
  - Save Delsys to the correct spot (refer to Delsys Standard Work Doc)
- OBS Recording
- Camera Recording

We will now have you complete a short virtual assembly survey about your experience.

- Begin the virtual assembly survey for the participant

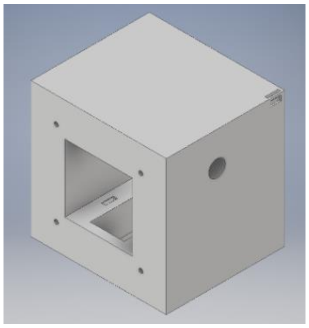
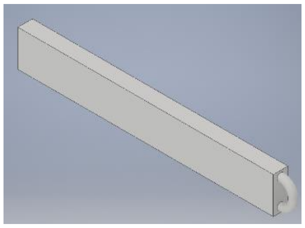
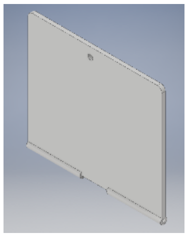
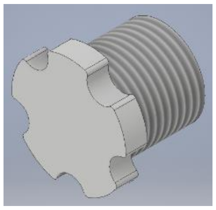
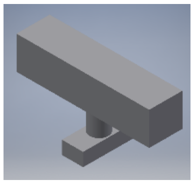
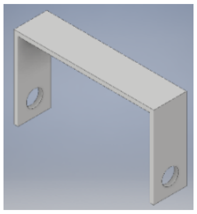
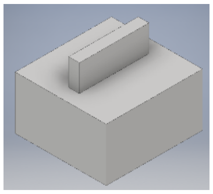
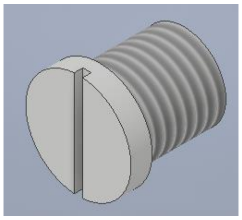
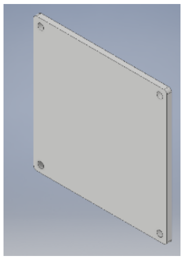
POST TRIAL

Post-Study Survey:

Finally, we will have you take a quick post-study survey about your experience, and you will be on your way!

Participant Debrief:
Thank you so much for partaking in this study! Your information will be kept completely confidential and your specific set of data will simply be referred to by your participant number assigned at the beginning of the experiment. Pay attention to the email you provided to receive your $20 e-gift card.

APPENDIX D: PEAT BOM

Part Name	Photo	Part Name	Photo
Main Base		Card	
Swivel Plate		Threaded Shaft	
Swivel Knob		Lifting Bracket	
Slider Block		Lifting Bracket Bolts (X2)	
Cover Plate		Cover Plate Bolts