A Comparison of Digital Human Model Ergonomics Outputs Driven by Optical and Inertial Motion Capture Systems in Virtual Reality

by

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The above committee determined that the thesis is acceptable in form and content and that a satisfactory knowledge of the field covered by the thesis was demonstrated by the candidate during an oral examination. A signed copy of the Certificate of Approval is available from the School of Graduate and Postdoctoral Studies.

ABSTRACT

Digital human models (DHM), or virtual human avatars, can be used within digital virtual manufacturing to conduct proactive ergonomics analyses. Recent technological advancements have allowed for dynamic posturing of the DHM using motion capture technology and virtual reality immersion, providing a potentially powerful approach to evaluate ergonomics outputs including hand location and spine compression. The purpose of this thesis was to compare the hand locations, joint angles and spine compressions produced by a DHM software program when driven by three different types of motion capture systems during a virtual reality task. Findings show that the inertial-driven model consistently underestimated hand locations by 24.3 cm, whereas the Vive trackers showed an overall RMS error of 13.7 cm. This error is further supported by spine compression values, where IMU-driven DHMs underestimated up to 213N compared to the optical system. As a result, the DHM generated using kinematic data from the Vive Trackers system provided the most similar results to the actual location and represent a promising, low cost solution for future ergonomics analyses.

Keywords: motion capture; virtual reality; proactive ergonomics; design; simulation

AUTHOR’S DECLARATION

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____________________________________ RYUTA DHARMAPUTRA

STATEMENT OF CONTRIBUTIONS

The research contained within this thesis was conducted in collaboration with Ryan Porto, Dr. Joel Cort, and Dr. Nicholas La Delfa. Ryuta Dharmaputra was the author of this thesis document and contributed to all aspects of this research, including design and conception of the study, in addition to the data collection and analysis.

All authors listed above contributed to the design of this thesis. **Ryan Porto** provided expertise in relation to the development, design, and equipment selection of the research study to generate relevant data for the automotive industry. **Dr. Joel A. Cort** contributed to the guidance of data processing and analysis. **Dr. Nicholas J. La Delfa** was primarily responsible for conceptualization of research design, guidance for data analysis and interpretation. In addition, Dr. La Delfa performed editorial modifications to this thesis document. However, the written content presented in this thesis is the work of myself.

I hereby certify that I am the sole author of this thesis and that no part of this thesis has been published or submitted for publication. I have used standard referencing practices to acknowledge ideas, research techniques, or other materials that belong to others. Furthermore, I hereby certify that I am the sole source of the creative works and/or inventive knowledge described in this thesis.

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LIST OF ABBREVIATIONS AND SYMBOLS

WMSDs	work-related musculoskeletal disorders
DHM	digital human model
VR	virtual reality
MMH	manual material handling
IMU	inertial measurement unit
VRMC	virtual reality motion capture
IR	infrared
HMD	head-mounted display
3D	three dimensional
CAD	computer-aided design
DOF	degrees of freedom
H	horizontal distance
V	vertical distance
L	lateral displacement
NIOSH	National Institute of Occupational Safety and Health
RMSE	root mean square error
MMJM	manual manikin joint manipulation
N	newtons
Hz	hertz

Chapter 1 - Introduction

Industrial work environments contain several physical exposures known to cause work-related musculoskeletal disorders (WMSD). These injuries can place a substantial financial burden on the industry, through lost productivity, decline of work quality; and both direct and indirect costs associated with compensation and return to work (Nur et al, 2014). Various ergonomics interventions have been developed and implemented to minimize the risk-factors and economic impact of WMSDs. Specifically, the risk of developing a WMSD at the lower back and shoulder increases when the demands of a work task exceed the capacity of the worker. This is also the case for repetitive work that requires force production at awkward positions (Snook, 1978; Marras et al., 2009). Awkward posture is defined by positions of a body segment that causes significant deviation from neutral positions (Jaffar et al., 2011). When in an awkward posture, muscles generally require higher activation to balance higher moment demands about the joints (Grieco et al., 1998). Common work tasks that require workers to position themselves awkwardly involve reaching movements, in which workers extend their upper extremities away from the body while exerting some force towards a certain direction. The field of ergonomics has continued to address the issue of reducing demands due to the increased prevalence of MSDs and to optimize production workflow (Bierwirth et al., 2012b).

Traditionally, ergonomics interventions are sought reactively, after a worker has already been injured. Proactive ergonomics is a field of study focused on conducting ergonomics analyses and recommending interventions early in the design process (White, 2015). Proactive ergonomics assessments often utilize digital human models (DHM) within a virtual environment that represents a work environment. This is defined as a simulation, where real-world work tasks and processes are replicated in a virtual setting for the purpose of analyzing and optimizing human performance before physical implementation. This method is conducted through the use of DHMs which are postured dynamically to perform each task in the virtual workstation. As such, ergonomics assessments, such as spine loading analyses and reach analyses can be conducted before a job exists in reality. DHMs are increasing in utility during the design processes as they reduce design-to-build time and costs (Zhang & Chaffin, 2005). Without proactive ergonomics, costs for changes at later developmental stages are more expensive compared to implementing changes during the design of the manufacturing process.

Recent advancements in technology have resulted in the capability of integrating immersive virtual reality (VR) into DHMs to eliminate the need for manual joint manipulation for work task design. Immersive VR technology is defined as the technology that gives a first-person perspective and fully engages the user's senses (sight, motion, sound, and haptics) in a virtual environment. This technology allows for an ergonomist or skilled operator to embody a DHM for posture manipulation and task simulation during the design process and, as such, has become a useful tool for simulating tasks for conducting proactive ergonomics assessments (Andrews et al., 2020). These tools have proven valuable in addressing limitations of traditional ergonomic assessments (e.g. manual joint manipulation, lack of real-time feedback, reliance on physical environments and prototyping, etc.). The use of motion capture technology partially addresses these issues, as kinematic data from real human movement can be used to posture the DHM in real-time, eliminating the need for traditional methods of manual joint manipulation keyboard and mouse to predict movement of a joint. This process is time-consuming and controls are challenging for unfamiliar users (Chaffin, 2005; Demirel et al., 2022). By combining motion capture with immersive VR, ergonomists and engineers can virtually embody DHMs to accurately simulate human movement, task design, and key ergonomics parameters, offering a more efficient and precise alternative to traditional approaches.

There are multiple motion capture systems that allow for kinematic data to dynamically drive the motion of a DHM. Two motion capture systems that are primarily used within the manufacturing industry are the inertial measurement unit (IMU) system and the optical infrared system. Optical infrared-based motion capture systems have long been used to conduct biomechanical analyses (Wang et al., 2012; Robert-Lachaine et al., 2019; Agostinelli et al., 2021; Tan et al., 2021). Optical motion capture systems, utilizing infrared and passive reflective markers, report sub- 2 millimeter system error for dynamic tasks and 0.2 millimeter system error for static tasks (Merriaux et al., 2017). This type of system is considered very high-cost, and although many manufacturing companies have used it in conjunction with DHMs to conduct proactive ergonomics analyses, a more cost-effective alternative, with a similar degree of accuracy, would be beneficial (Qing et al., 2017). The increased use of IMU systems over the past ten years have shown potential to become an alternative to the optical motion capture system; however, various limitations to IMUs continue to persist, limiting its adoption in the ergonomics and manufacturing industries. An example of one IMU system, the Movella Xsens MTw Awinda, uses accelerometers to determine their relative position between each sensor based on segment length estimations derived from anthropometrics previously inputted into its native software. The accuracy of this software, pertaining to upper limb joint angles and positions, independent of DHM use, indicates high accuracy with a Pearson correlation of 0.75 to 0.99 compared to an optical measurement system (Chung et al., 2011; Robert-Lachaine et al., 2017) as well as joint angle RMS errors of up to 10 degrees when compared to an established biomechanical model (Schepers et al., 2018). However, this accuracy does not necessarily translate when used as an input for DHM dynamic posturing (Sfalcin et al., 2019). Further investigation needs to be conducted to find the source, and to quantify the magnitude of this discrepancy. This integration of technologies is revolutionizing the way ergonomics parameters are evaluated and optimized in the industrial setting. However, issues within each of the two technologies exist when used alongside the *Process Simulate* DHM, including questions related to accuracy, cost, connectivity and compatibility; all of which have hindered widespread adoption (Grajewski et al., 2012; Rizzuto et al., 2019; Malik et al., 2020).

This thesis examines the use of different motion capture technologies as a body tracking method for virtual reality posturing and ergonomics analysis of a DHM (Siemens *Process Simulate*). Specifically, the thesis aims to compare the hand locations produced by a DHM in virtual reality, compared to a ground truth location of the hands. Three different methods for driving the DHM's motion in VR will be compared, including optical motion capture (Vicon), wearable inertial motion capture (Xsens) and a combined (optical and inertial) approach linked with VR technology (Vive Pro 2 and Vive Trackers 3.0). The findings of this study will help the manufacturing industry understand the performance of each motion capture system in combination with *Process Simulate,* for virtual ergonomics use, and identify conditions in which these systems may not be suitable to base their decisions upon. This study will also help inform selection of human models driven by various motion capture systems within the DHM software package: *Process Simulate* for proactive ergonomics use within the manufacturing industry. This study will also contribute to risk mitigation in ergonomic evaluation, minimizing risks due to errors and inaccuracies depending on specific demands of certain applications positively impacting the decision-making process in ergonomics.

Chapter 2 - Understanding Real-Time Motion Tracking in Proactive Ergonomics Analysis: Literature Review

2.1. Introduction

Work-related musculoskeletal disorders (WMSDs) are any musculoskeletal injury that takes place while performing an occupational task. The risk of developing a WMSD is further increased when the demands of a work task exceed the capacity of the worker (Snook, 1978). WMSDs result in a loss of productivity and degradation of work quality and are most associated with significant increased costs within the industrial field while unnecessarily adding more financial burden to the healthcare system (Marras et al., 2009; Nur et al., 2014). Specifically, the trunk and upper extremities are the regions of the body reported to have the highest injury rates, including, but not limited to, the lower back, shoulders, and hands (Association of Workers' Compensation Boards of Canada, 2020). Total economic costs of WMSDs are difficult to quantify, but an estimated cost of both back and upper extremity injuries in the United States are reported to be around $66,000 and $6,250, respectively (Kaur et al., 2021). In 2019 alone, 271,806 workplace injury claims were reported in Canada (Tucker & Keefe, 2021) with around 15% occurring within the manufacturing sector. Reducing the prevalence of workplace injuries starts with the identification of risk factors.

This literature review was conducted to understand physical risk factors for WMSD, followed by how motion capture and virtual reality technologies have been used to proactively identify WMSD risk factors and optimize industrial work tasks. The ultimate goal of this review was to understand the current state of proactive ergonomics interventions; namely: immersive virtual reality and digital human modelling (DHM) software using these various motion capture techniques.

2.2. Physical Risk Factors of Work-related Musculoskeletal Disorders

Work-related musculoskeletal disorders (WMSD) are injuries that affect ligaments, muscles, tendons, nerves, and blood vessels of the body, sustained during occupational tasks. They are the leading type of occupational injury in North America which heavily impacts workers' health and productivity, and incur great losses for the workers' compensation system. Physical risk factors that contribute to WMSD include high repetitive motions, increased force exertions, awkward postures, and prolonged static positions. These risk factors significantly increase muscular demand, commonly leading to injuries (Gallagher & Heberger, 2013). Common manufacturing assembly tasks involve manual material handling (MMH), such as lifting, lowering, pushing, and pulling.

A common motion associated with MMH tasks involve extended forward reaching. Forward reaching involves extending the elbows anterior to the torso, elevating the shoulder joint, and possibly flexing the trunk at times. Continuous repetitive reaching, while simultaneously applying force at an awkward position, increases mechanical stress on the muscles, tendons, and/or ligaments, which increases the risk for strain-related injury over time (O'Neil et al., 2001). Increased biomechanical loading during horizontal, vertical, and asymmetrical reaching tasks can lead to increased spinal compression, making these movements significant physical risk factors (Jäger & Luttmann, 1992). As such, evaluating horizontal, vertical, lateral, and asymmetrical reaching in MMH tasks are critical factors when conducting an ergonomics task analysis, as these parameters generally scale with biomechanical joint loading (Harari et al., 2019). Increasing horizontal distance of the load (i.e. the hands holding some object) from the spine also further increases spine compression and shear loading (Snook, 1978). Decreasing the vertical distance of the load to the ground increases lumbar spine stress (Chaffin, 2005). A combination of asymmetrical reaching and trunk flexion increases spinal compression and lateral shear, whereas anterior-posterior shear decreases with asymmetry (Marras & Davis, 1998). Given the relationship between hand location (and therefore reach distance) and spine loading, accurate quantification of hand locations are critical measurements required to calculate spine compression (Garg et al., 1991). Ultimately, exceeding spine compression tolerances can cause structural damage, increasing risks of injury to the disc, nerves, and bones while also causing discomfort to a worker (McGill and Norman, 1986; Waters, 1993).

Similarly, spine and shoulder loading also increases as the load is placed further away from the midline of the body. When loads are laterally displaced (moved to the left or right of the sagittal plane of the body), asymmetry in load placement causes an increased force demand of the hand nearest to the center-of-gravity of the load and lateral bending of the spine, resulting in the decline of MMH capabilities (Mital et al., 1997). As such, it is important to consider these parameters when conducting various types of ergonomics assessments. There are certain common occupational postures during manual work which can excretable both spine and shoulder loading exposures. Some of these conditions, including forward trunk-bending and extended reaching, will be described further in the following sections.

2.2.1. Trunk-Bending Posture

Movement that requires trunk-bending is defined by abduction and overextension of the arms away from the body in combination with scapular rotation, trunk rotation, and trunk flexion. This position further requires higher muscular force to maintain balance and stability in addition to the already demanding repetitive work task (Jaffar et al., 2011). Leaning on an external object, with contact around the pelvis or the upper legs, can help reduce low back tissue loading (Fewster & Potvin, 2015). Workers tend to lean to better support their body while completing trunk-bending reaching tasks. Leaning of the free arm while reaching externally supports the bodyweight, providing better stabilization of the initially awkward reaching position. Bracing the trunk while bending could also increase stabilization of the spine, further reducing tissue loading for a short period of time (Fewster & Potvin, 2015). Although design interventions and ergonomics assessments have allowed for reductions of these tasks, static trunk bending is still an occupational risk factor for development of lower back injuries over time, which is still the most common region associated with the development of WMSD. Understanding where the hands are in relation to the body (i.e. horizontal and vertical locations) are important predictors of WMSD risk that can be utilized to design work tasks with lower physical exposures to the spine and shoulders (Waters et al., 1993).

2.2.2. Extended Reaching Tasks

Manufacturing assembly tasks often involve repetitive upper limb reaching of tools and parts placed at a workstation. Tools are often placed in an area that requires full arm extension to reach, pivoting around the shoulder (Sengupta & Das, 2010). This is known as the working reach envelope, an area in which an individual can comfortably reach for an object while maintaining minimum arm deviation from neutral position. Reaching at extreme positions, within and outside of the reach envelope, significantly increases the loading exposure on the shoulder, while concomitantly reducing strength capability (La Delfa & Potvin, 2016). Repetitive reach above a shoulder elevation angle of 90° is a main factor of shoulder injury and subjective whole-body discomfort (Lin et al., 2009). Arm reaching at an MMH workstation will always occur even when a workstation is designed with parts and tools within the immediate reach envelope. Using virtual simulations to predict and design for arm reach within a workstation could help design to minimize extended reaching in a task.

2.3. Types of Ergonomic Interventions

Various ergonomics interventions continue to be implemented to minimize physical risk factors and the economic impact of WMSDs (Marras et al., 2009). These ergonomics programs should be designed to maximize productivity, efficiency, quality, and worker comfort while also addressing potential WMSD risk factors (Marras & Karwowski, 2006). Ergonomics interventions are commonly categorized into two different approaches depending on the relative timing of their implementation. A reactive ergonomics approach involves introducing interventions into an existing workspace to reduce health risks in response to reports of discomfort or injury. Essentially, reactive ergonomics is implemented after significant problems or injuries have occurred. Although less effective due to financial, time, and flexibility constraints, this approach is often necessary in dynamic work environments where conditions frequently change. Common methods in this approach include administrative adjustments, such as increasing breaks, hiring additional workers, or modifying work techniques (Marras & Karwowski, 2006).

Contrary to the reactive ergonomics approach, a proactive approach focuses on early identification of risk factors. In a proactive approach, potential hazards can be mitigated or eliminated through engineering and administrative controls implemented early in the design process, before the job ever exists in reality. This process decreases potential physical stressors while also optimally designing for productivity (White, 2015). A proactive ergonomics approach also has financial benefits, as injuries are less likely to occur when a workstation is designed specifically for the worker, while also allowing for adjustability during the design process as shown in *Figure 2.1*. Ergonomics analysis during this process typically relies on the use of a computer-aided design software in which a virtual workstation can be created as a digital prototype.

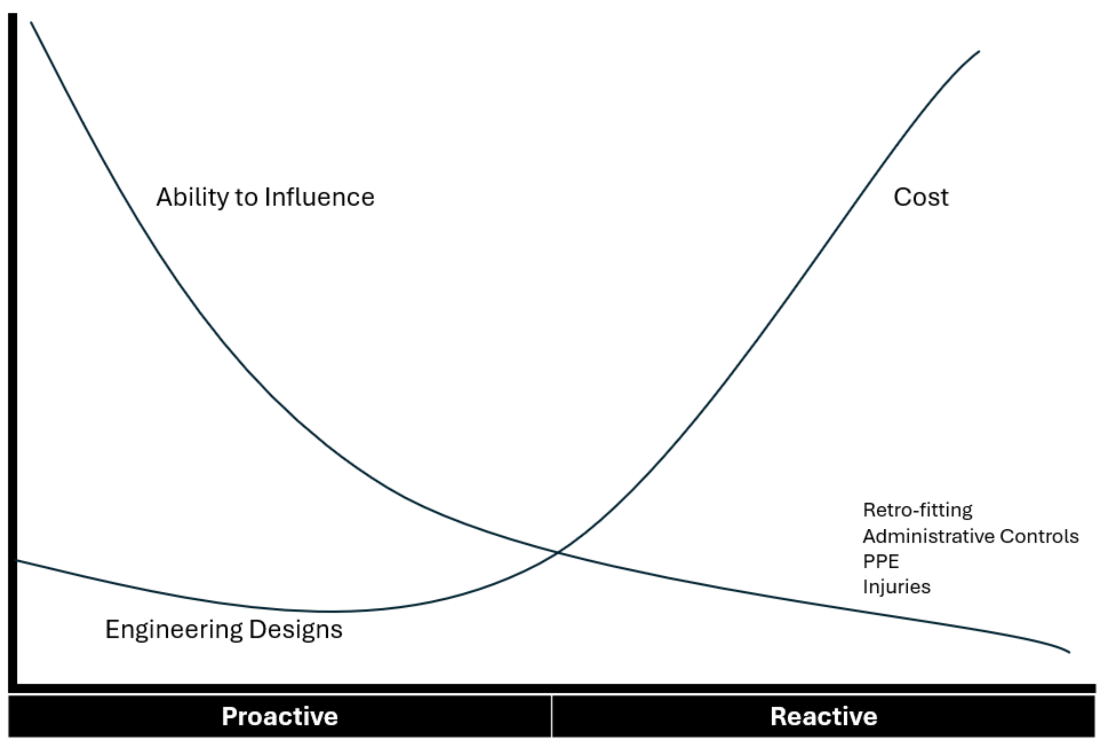

Figure 2.1: Comparison of strengths and limitations between proactive and reactive ergonomics interventions, where proactive ergonomics have an increased ability to influence engineering designs with low costs. These costs increase during reactive ergonomics, and

changes to a task can only be done through administrative controls, retro-fitting, implementing personal protective equipment (PPE), and/or after injuries have occurred (White, 2015).

The use of DHMs to conduct ergonomics analyses has continuously been done from as early as the 90's (e.g. 3DSSPP, EDS-PLM, RAMSIS). Early DHMs focused on static postural analyses and basic ergonomics assessment which provided critical insights into how user populations could perform reaching, fitting, lifting tasks without discomfort or risk of injury. These models enable designers to evaluate human interaction with workspaces during the early design phase to mitigate the need for physical prototypes. The tools initially relied on simple geometric and biomechanical algorithms, limiting early usage to static conditions of reach and fitting tasks (Chaffin, 2001). As technology progressed, dynamic aspects of human motion were integrated into DHMs. Methods such as functional regression models were implemented to predict joint angles and body segment trajectories during work task simulations. These methods were enhanced by integrating real motion capture data to improve accuracy and reliability of simulations. Motion capture systems provide high-resolution data about human movement enabling DHMs to simulate task-specific behavior, such as workspace navigation and tool usage. Further technological advances in integrating immersive virtual reality and 3D virtual CAD environments allow for users to experience a virtual workplace in real-time through the lens of a digital human model.

More recently, the integration of virtual reality and motion capture technologies into a digital workstation design has seen to increase efficiency from a product design, product realization, monitoring, and optimization of the production process. Preventive evaluation of virtual workstation design reduces time and costs with adjustability in design parameters without risks (Caputo et al, 2018). Two factors to be considered when conducting a proactive ergonomic analysis would be psychophysical factors and anthropometric parameters of the potential worker. The anthropometric parameters of a worker's body segments are another fundamental factor to consider when designing a workstation and task to fit the worker's physical dimensions. These physical characteristics are defined by the length, mass, girth, and width measurements of a populations' body segments. Considering these parameters during the workstation design process could reduce risk factors to the development of a WMSD while also increasing productivity by matching the worker population's dimensions for tool, equipment, or furniture use (Nicholson, 1991). Anthropometric data are used in conjunction with ergonomic assessment tools such as digital human modelling and virtual environment design tools to predict any injury risks for reach, clearance, position, and strength during the workstation design (Dianat et al., 2018).

2.3.1. Digital Human Modelling (DHM) Software

A modelling tool used to simulate a worker within a virtual environment is known as a digital human model (DHM). DHM's typically include a linked-segment skeletal model that couples segments with joints to create a virtual replica of a worker. Using a DHM allows for a better understanding of injury risk in relation to a virtual prototype of a workstation while also integrating ergonomic assessments during pre-production planning and designing process. The surface of the model is a representation of the skin and clothing with 3-dimensional textures to imitate the real world. Using inverse kinematics algorithms, DHMs are reliable when used to detect static postural strains, but dynamic movement with forces greater than 30N at extreme joint angles prove to be more difficult to estimate due to current limitations of human modelling software (Fritzsche, 2010). A worker's anthropometric parameters can be entered into a DHM software program to simulate a target population's physical dimensions based on various anthropometric databases. Utilizing the target population's anthropometric characteristics allowing for a more accurate representation of future workers during the design process of a workstation (Kajaks et al., 2011). Task parameters, such as load horizontal distance, load vertical distance, reach envelope, hand clearance, etc., can be evaluated for a worker's posture during simulations using DHMs (Schaub et al., 2013).

Computer-aided design (CAD) involves the utilization of computer graphics to assist with designing a workplace or product CAD software is most notably used by engineers and designers to create a virtual prototype of a product or a workstation. 3D designs of realistic objects, that will be present in a workplace, are inserted into the virtual environment, creating virtual workstations that are easily adjustable. When used in conjunction with digital human modelling, a simulated interaction between the worker and the digital environment can be created to study various design and ergonomics implications. While successful and widely accepted when conducting postural analysis, ergonomic analysis for dynamic interactions between the digital human model and the virtual work environment is still in the early stages, requiring more validation and research (Mukhopadhyay et al., 2012). One factor to be considered when conducting an ergonomics analysis during the design of a workstation is the potential spinal compression a task requires of the worker (Pope et al., 2002). This is because repeated exposure to spinal compression that exceeds the spinal compression tolerance limit results in an increased risk of spine-related injury (Genaidy et al., 1993). Predictive equations and assessments have been developed to calculate potential spinal compression for various work tasks during the design process. Equations are used as a means of assessment to determine the acceptable physical demands when designing workstations for repetitive tasks (Potvin, 2012). These recommendations are often based on the anthropometric parameters of the targeted workers to fit the workstation.

Posturing a DHM has traditionally been done using manual manikin joint manipulation (MMJM), where the user painstakingly manipulates each joint of the manikin to recreate a task frame-by-frame (Kajaks et al., 2011). This method of manual posturing of DHMs is inconsistent, time-consuming, and inaccurate without a point of reference (McInnes et al., 2009; Fritzsche, 2010). The use of motion capture technologies in combination with immersive virtual reality has allowed for human models to be postured using previously collected 3D kinematics data. More recently, motion capture technologies have introduced real-time body tracking in DHMs for a more realistic task analysis experience. This experience is further enhanced with the use of virtual reality technology, allowing users to embody the DHM and simulate tasks as if they are performing them in physical reality. It must be noted that assessments using immersive VR alone are unable to completely evaluate and predict work tasks, as accuracy and precision issues, as well as considerations for common psychosocial factors within a workplace are still present (Rizzuto et al., 2019).

Lastly, there is a wide variety of commercially available DHM software packages that can be used to conduct ergonomics analyses. Some examples include *SantosHuman*, *SAMMIE*, *3DSSPP, Delmia, Siemens Jack, Siemens Tecnomatix,* and many others. The *Process Simulate* software package by Siemens has integrated its native DHM software (*Jack)* into a computer-aided design (CAD) software, enabling sophisticated DHM ergonomics analyses, with integration of leading motion capture and virtual reality technology for real-time analysis. As such, this software package has strong usage amongst several ergonomics and design programs within North America and will be the DHM platform utilized within this thesis research.

The *Process Simulate* software package is a manufacturing process design software capable of simulating, validating, visualizing, and optimizing manufacturing processes in a virtual environment. It enables users to design and test assembly lines, robotics, factory layouts, workstation design and along with its digital human model, SIEMENS Jack™, biomechanical and ergonomics analyses of human interactions with equipment within a virtual workspace. This software is widely used in manufacturing industries such as automotive and aerospace to help reduce costs, injuries, and increase production efficiency and as such, is determined to be the industry standard process design and DHM for proactive ergonomics assessments(Qi & Chen, 2020; Frietzsche, 2010; Naddeo et al., 2018). In its core, this software is a process design software, with established CAD and robotics design functions, however body tracking integrations that drive DHMs are still in continuous development. As such, challenges in joint deviations and pose estimation analysis continue to rise when creating virtual dynamic work task simulations (Ji et al., 2021). This issue should be addressed as the current long-term goal for ergonomists is to simulate dynamic human movement with minimal use of manual joint manipulation through traditional methods. Although motion data by various motion capture systems are able to be streamed into *Process Simulate* to drive its DHMs, accuracy issues continue to remain as multiple layers of modelling and estimations occur during this process. As of *Process Simulate* version 2307, integration of virtual reality and body tracking is present in order to drive the DHM from a first-person perspective. However, as of right now, the only integrated VR hardware for use is the HTC Vive systems along with its Trackers 3.0 (Siemens PLM, 2024).

2.4. Immersive Virtual Reality (VR)

For the past ten years, the utilization of virtual reality as a means for complex ergonomics analyses has continued to be assessed in minimizing WMSD risk factors (Kaemi & Lee, 2023). As a form of proactive ergonomics intervention, immersive VR allows for design and posturing of a DHM within a work task simulation in first-person perspective resulting in the possibility of a collaborative design process between engineers and ergonomists to analyze and identify potential biomechanical hazards within workstations. This approach can reduce production and productivity costs during the development phase as immersive VR environments replace the need for physical prototypes of workstations to be built by early detection of ergonomics hazards present in the design of a workstation (Backstrand et al., 2007; da Silva et al., 2022). Users can recreate human postures and simulations of human movement in a virtual setting, which enhances the accuracy of simulating work tasks. The real-time simulation of human movement of the DHM within a virtual environment allows for immediate ergonomics feedback and analysis when conducting design of a workstation. Current and previous iterations of VR head-mounted displays can produce high resolution images without compensating for visual refresh rate, while also providing a wide field-of-view. The HTC Vive Pro 2 and its bundled motion capture system, the Vive Trackers, were selected for this literature review specifically, as it is what is currently recommended by *Process Simulate*, as well as the most commonly used headset for proactive ergonomics analyses in the automotive and aviation manufacturing industries. There are, however, various limitations associated with utilizing VR for work task simulation. Primarily, depth perception and horizontal distance estimation between the user to an object within the virtual environment is inconsistent and distorted (Otto et al., 2019). Distance underestimation from a target is primarily caused using motion parallax to define egocentric depth perception (Vienne et al., 2020). Motion parallax is a depth perception cue present in immersive virtual environments in which objects seem further than where they are in the virtual space. Objects closer to the viewer result in a larger displacement compared to objects further away, especially when the object is being manipulated. The presence of motion parallax is relatively valuable to path tracing tasks but is inconsistent in visually guided reach tasks (Eftekharifar et al., 2020). Depth perception exists in every virtual environment, but specifically influences perceived distance in immersive HMD VR systems.

On specific one-arm reach tasks, body kinematics of those in immersive VR technology somewhat mimics movement of the real world with some positional error. Earlier evaluations of VR technology showed a 60 mm hand positional error and joint angle deviations when comparing immersive VR (the HTC Vive system) to the real world (Thomas et al., 2016; Vox et al., 2021). This is important for implementation of VR technologies for proactive ergonomics analyses using a DHM, as errors could influence other ergonomics parameters (e.g. spine compression, hand clearances, joint loading), further affecting decisions to be made regarding task acceptability. Differences in target error vary in range but are always present when compared to a physical reality condition (Rizzuto et al., 2019). It is important to note that differences in joint angles were also present in this comparison as movements conducted in VR showed an increased angle of movement at the hip, spine, and shoulder, but does not seem to be affected during static endpoint posture analysis. In addition to increased target error, the exaggeration of joint angles, especially at the upper limb, is also present due to underestimation of the target location (Penumudi et al., 2020). Underestimation of distance perception is present when the user is not in a static state while presented with live events through the HMD (El Jamiy et al., 2020; Jones et al., 2011).

Another limitation of immersive VR HMDs is the potential conditions that could worsen in potential users such as susceptibility to motion sickness, active nausea, epilepsy, recent and/or severe brain trauma (Birckhead et al., 2019).

2.5. Motion Capture to Quantify Musculoskeletal Kinematics

Motion capture is a technique used to record human body movement through capturing positions and orientations of body segments within a 3-dimensional space. Another emerging technology within the motion capture field is the use of computer vision for markerless tracking. This technology, however, has not yet been integrated into the *Process Simulate* DHM software, and thus could not be evaluated. Focusing on motion and kinematics, such as positional data, velocity, and acceleration, kinematic motion capture typically involves the use of markers or trackers affixed to anatomical landmarks on a person's body. These markers are tracked by other sensors as the human moves, reconstructing a person's movements within a virtual 3D environment. Translations and rotations of joints, limb segments, and the whole body are accurately quantified to provide better understanding of biomechanics. Kinematics data provided by motion capture serves as a key input for biomechanical models, allowing for task simulations and proactive ergonomics assessments. Biomechanical models created from motion capture positional data serve as a tool to simulate a worker's posture and movements when conducting tasks. Postures and movements within a digital environment can then be recreated with DHM software for evaluation of how the human body interacts with designed workstations, tools, and environments. Motion capture technology has continued to evolve over the years, producing more affordable, accessible and accurate, solutions to collecting kinematic data. There are various types of motion capture systems with different fundamental approaches for capturing kinematics data.

2.5.1. Optical-electronic Motion Capture

Optical-electronic motion capture technology is known for its accurate and precise measurements. With sub-two millimeter system error when collecting both static and dynamic movements (Merriaux et al., 2017) these systems are widely used in research, entertainment, and occupational practice. These systems use high-speed cameras in conjunction with infrared (IR) sensors to track the positions of reflective markers placed on an object or human in real-time. Each marker reflects the emitted IR light, allowing the host system to calculate each marker's specific location within a calibrated 3D-space. This positional information is then used to reconstruct movements of the individual in a virtual environment. Marker placement templates vary depending on the purpose of data collection, from specific segments to full-body data acquisition including finger and object tracking. A subject model is created or sampled by the user before replicating the collected movements in the virtual environment. Because of this flexibility and accuracy, it is often considered to be the "gold standard" for motion analysis in the literature (Kruk & Reijne, 2018). There are numerous commercial Optical systems available in the market, each with their own respective pros and cons: *Vicon MX*, *OptiTrack Prime*, *Qualisys Oqus*, *Motion Analysis Raptor* (Topley & Richards, 2020). However, it is to be noted that although the most accurate, the optical motion capture system is not affordable and, as such, other alternatives are being investigated to provide similar results with lesser costs.

Figure 2.2. *Top left*: A Vicon Vantage camera, able to sample sensor motions at 420 Hz, and a resolution of 2432 x 2048. *Top Right*: A Vicon Nero camera, able to sample motions at 330 Hz, and a resolution of 1920 x 1080. *Bottom*: Reflective markers placed onto the surface of joint segments tracked by aforementioned cameras to determine kinematic information.

Optical systems are often regarded as the most feasible and accurate system for biomechanics and ergonomics research. This is due to the delicate nature of biomechanical analysis of human movement. Optical systems offer advantages such as low latency, high-capture resolution allowing up to 4096x4096 sensor resolution, and high-frequency sampling capabilities, with several systems capable of reaching 10,000 Hz capture rate (Topley & Richards, 2020). In ergonomics, Optical systems have been used in proactive occupational task and posture analysis in a laboratory setting, by using these kinematics data to posture a DHM manikin to design and improve worker processes while capitalizing on both operator knowledge and expertise (Geiselhart et al., 2016; Grandi et al., 2024). Kinematic information provided by optical systems can be used to calculate tissue loading and indicate muscle fatigue through anthropometric formation (Whitaker et al., 2018), which is integral in enabling both proactive and reactive ergonomics interventions.

Though commonly thought of as the gold-standard for biomechanics research, there are some limitations to optical systems. A limitation of the optical motion capture system is the fixed location of the camera system, meaning data acquisition can only occur in a restricted area (Begon et al., 2009). Optical systems' capture volume is dependent on the field-of-view and number of cameras that are present within the limited area. As such, practicality, cost, portability, synchronization, and calibration are all limitations that must be considered before deciding to collect kinematic data from an Optical system system. Another major limitation is the potential for visual obstructions, where the reflective markers are blocked by the body or other structures in the capture volume. This can be a particularly challenging limitation in ergonomics research, where participants are often interacting with large objects, or ingressing or reaching into vehicles (or simulated vehicles in a lab setting), sometimes causing complete kinematics obstructions. Other motion capture technologies that address these limitations have emerged.

2.5.2. Inertial-Measurement Unit (IMU)-based Motion Capture

IMU-based motion capture relies on the use of inertial sensors such as accelerometers, gyroscopes and magnetometers to capture human and/or object movements. IMU systems operate independently, without requiring fixed cameras or external recording devices, providing a unique advantage relative to optical-based systems when portability is required. This portability makes IMU systems ideal for use in environments where freedom of movement is essential and minimal equipment is required, such as manufacturing workstations, outdoor sports, and clinical applications.

Multiple IMU sensors (e.g. Movella Xsens MTw Awinda, Noraxon Ultium Motion, Vicon Blue Trident) capture acceleration, angular velocity, and electromagnetic orientation to re-create body movements in real-time using a biomechanical model of limb segments previously calculated using anthropometric data inputs. Inverse dynamic kinematic analysis, where Newton-Euler equations are applied sequentially to body segment kinematics allow joint loading calculations (Menolotto et al., 2020). Limitations of using this method is that it will be highly dependent on anthropometric data measured to recreate a biomechanical model based on its calculations. IMU systems generate biomechanically relevant data through the fusion of sensor data from multiple modalities. Accelerometers are used to measure sensor vertical direction by sensing acceleration relative to gravity. Once gravity is removed, the vector of linear acceleration can be double integrated to acquire the position of each sensor as well as its position to recreate a biomechanical model. Magnetometers sense the direction of the earth's magnetic field in the horizontal plane. Rate gyroscopes are used to measure change in angle through integration of angular velocity over time (Roetenberg et al., 2009). Sensor kinematics are calculated from the information collected using an inertial navigation algorithm, predicting sensor position and orientation. Joint origins for body segments, calculated from the inertial navigation algorithm, are used to define joint angles based on ISB recommendations for reporting kinematic data (Wu et al., 2005). A biomechanical model can then be defined from this information. For example, the biomechanical model used by the Xsens Awinda system (the commercial system used in this research project) consists of 23 segments: pelvis, L5, L3, T12, T8, neck, head, shoulders, upper arms, lower arms, hands, upper legs, lower legs, feet, and toes. Body segments without specified sensors are estimated using connected segments within the biomechanical model (Schepers et al., 2018).

The main advantages of IMU systems are considered to be their ease of use, affordability, and portability. Because IMU systems do not require the use of a fixed camera system to track motion, set-up can be performed at any location if they are close to the host station and receiver. User set-up only requires donning of sensors and calibration. A calibration is required for the system to orient the sensors relative to one another when affixed to each participant's unique anthropometry, then a generalized biomechanical model is scaled to the measurement input parameters provided. Afterwards, the alignment between sensors and segments is obtained through standing still in an N-pose before moving around (e.g. XSens Awinda). IMUs are more affordable than most high-accuracy optical systems with full-body tracking bundles priced at around $45000 as opposed to the minimum of $150000 for a full 10-camera optical tracking system. It also allows for unrestricted use of space if sensors are within reasonable distance from the base station. More advanced systems even allow for data logging within the sensors (e.g. XSens Link), allowing subjects to travel completely unrestricted by proximity to some base recording station. This level of portability allows for kinematic data collections at naturalistic settings, increasing ecological validity of research.

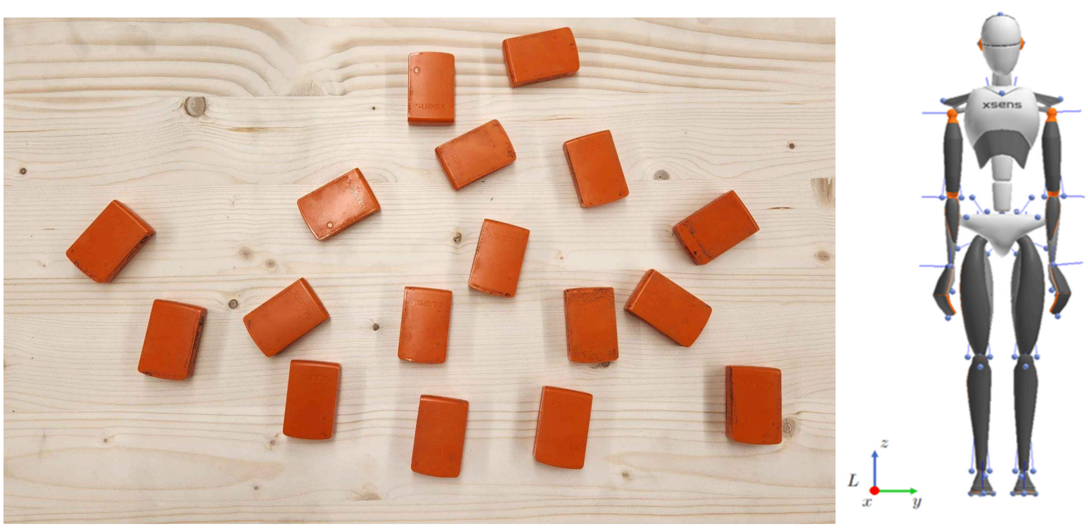

Figure 2.3. *Left*: All 17 Xsens Awinda IMU sensors, each containing an accelerometer, gyroscope, and magnetometer. Each sensor is placed on specific segments labeled on each

sensor’s surface. *Right*: Biomechanical model generated in the Xsens MVN host software from full-body IMU motion capture data.

Despite many of the distinct advantages for ergonomics evaluation, there still are some important limitations of IMU-based systems. Other limitations related to these systems are the presence of signal drift and inaccuracies at extreme joint angles during rapid reach movements (Sfalcin et al., 2019; Roetenberg et al., 2009; Schepers et al., 2018). Due to the process of data collection using accelerometers, integration drift is present when determining position of the sensors. Over a short time, accurate acceleration, velocity, and displacement data can be obtained, but over time will drift due to sensor and direction estimation errors. This issue is solved by incorporating contact detection algorithms to estimate relative position and orientation of each individual body segment, as well as position of the body in the environment. However, sensor errors could still be present as the connection between a sensor and the body segment fluctuates due to soft tissue artifacts. More recent iterations of IMU systems have formulated advanced models that account for these issues by utilizing additional aiding mechanisms (e.g. XSens Awinda plus a Vive Tracker).

Overall, IMU systems have become a popular option for ergonomics applications and have seen strong recent progress towards solving some of the limitations of sensor drift. Research is ongoing to validate the accuracy of kinematic data from these IMU systems compared to optical systems, which are typically treated as the gold-standard due to their high accuracy and precision. There are various forms of IMU systems available in the market that combine accelerometer, magnetometer, and 3D gyroscopes (e.g. XSens, Noraxon). In the ergonomics industry, advantages of IMU systems allow for kinematic analysis at various workplaces without requiring camera setups and the near certainty of visual occlusions. The literature suggests that IMU systems are the most researched and used motion capture system within manufacturing industrial applications to improve workers' health and increasing productivity (Menolotto et al., 2020). There are various ways to conduct ergonomics assessments with the use of IMU systems, mainly rapid assessments such as the Rapid-Upper Limb Assessment (RULA), or the Rapid Entire Body Assessment (REBA). However, these analysis tools represent basic ergonomics risk categorization and do not utilize the full potential of the kinematics data being captured. As such, integration of motion data into DHM software is a new avenue for utilizing IMU technology that can allow for more advanced exposure assessments, by specifically computing joint torques and spine compression using full-body motion capture in field settings (Fischer et al., 2023; Ji & Tiari, 2022; Ji et al., 2022).

2.5.3. VR-Based Motion Capture (VRMC)

A more recent development in the motion capture space is the use of VR-based motion capture (VRMC) systems such as the HTC Vive Trackers and the Vive Pro 2 HMD. The Vive system tracks and translates real-world movements into a virtual environment through use of VR head-mounted display (HMD) systems and various trackers placed on other body segments. This system utilizes both 9-degrees-of-freedom inertial measurement units and optical infrared rays shot out by base stations at each corner of a space to pinpoint the locations of the sensors located in each tracker (HMD, tracker, and controllers). VRMC systems are used when real-world objects need to be simulated within a VR environment. These include use-cases such as sports simulation for athlete training, film production, professional simulations for occupation-specific training, health rehabilitation, and collaborative manufacturing design. Many use cases in the health and entertainment industry have reported successful outcomes when using VRMC systems to improve quality of limb segment visualization (Hara et al., 2018; Adolf et al., 2019). For integrated use with a DHM for proactive ergonomics analysis in a manufacturing design setting, however, VRMC systems are not generally recommended to measure joint angles, as deviations of between ±6° and ±42° were present (Vox et al., 2021).

The most common VRMC system used in the ergonomics field that is currently available in the market is the *HTC Vive Tracker 3.0* (Borges et al., 2018; Goncalves et al., 2021; Zuk et al., 2022). The HTC Vive series and other optical-aided VR systems utilize photosensors located in trackers, HMDs, and controllers that sense infrared rays emitted at a 45° angle over a time sequence from SteamVR Base stations. Base stations act as "lighthouses" that emit infrared ray sweeps over a timely sequence in which photosensors in each peripheral (the trackers, controllers, and headset) are pinged. In order to determine where a tracked peripheral is in space, time-position previously pinged by the photosensors in each peripheral is referred to the calibrated room set-up. It is a part of the HTC Vive VR system and has the same hardware requirements as other components of the system. These trackers transmit coordinate information when they come into contact with the infrared rays emitted by the base stations, allowing the host computer to recreate the tracked object in virtual reality, making it interactable. These trackers allow for pose estimation independently by each tracker relative to the room coordinate system previously calibrated (Zuk et al., 2022). While previous research has focused on measuring accuracy during movements using robotics, there is a need for validation specifically emphasizing the use of these trackers on humans. Merker et al. (2023) showed that rapid, high velocity movements with greater than 600 m/s^2 led to a delayed change of direction due to both the limited sampling rate of wireless transmission of 90 Hz, and the double integration method of calculating displacement. This is a limitation as more industries requiring highly accurate measuring systems flock to the use of VR in the industry. Previous and current iterations of these trackers have been validated and compared with an optical system, mainly focusing on comparison of positional accuracy, and detecting movement trajectories. Even so, the system produced sufficient measurement accuracy for visualization within VR and measured static joint segments using inverse kinematics. As such, when integrated into a DHM, this system could still provide biomechanical insights for ergonomics analyses, as a biomechanical model would be generated from each tracker's independent inverse kinematics data (Grandi et al., 2024).

Figure 2.4. An image of an immersive VR bundle comprising the HTC Vive Trackers 3.0, Vive controllers, and the Vive Pro 2 HMD from left to right.

Compared to other motion capture systems, the HTC Vive Trackers are more accessible and affordable as they also use the same method of tracking with VR-HMDs (e.g. HTC Vive, Valve Index). Ease of use is another advantage of VRMC systems, as a reasonable number of sensors (usually six) are easily mountable and placed on body segments using straps. Integration into various applications is also possible as tracking is all performed by the SteamVR application, which is an open source platform that serves as a hub for integrating and managing VR applications and hardware. This allows users to access simulations, applications, and games created by developers of various platforms. The most recent iteration of the HTC Vive 3.0 Trackers is accurate enough to visualize limb segments within a virtual reality environment. However, whether these limb segment representations can extend beyond just realistic visualizations, and into the realm of biomechanical analysis, remains to be seen. One potential issue is that the reference plane used by the Vive Tracker system is often tilted away from the true ground plane, causing inconsistent orientation and direction measurements. As a result, whenever headset and trackers are occluded, orientation of the reference ground plane would slightly change, impacting orientation of the user being tracked (Niehorster et al., 20217). Additionally, the presence of vibrations generated by the photosensors within each tracker can cause IMU drift over time, resulting in stuttering during rapid movements. The HTC Vive tracker set, consisting of trackers, controllers, and the HMD, as shown in *figure 2.2*, provided high precision with a root mean square deviation of less than 0.55mm and 0.12° on both static and dynamic movements. However, trajectory and velocity accuracy were found to be unreliable at higher velocities, rendering it less viable for dynamic performance (Ikbal et al., 2021; Merker et al., 2023).

Limitations to usage of the VRMC (specifically the HTC Vive Trackers), include potential occlusions of the HMD, trackers and/or controllers from the base stations. *Process Simulate* recommends a 4-base station set up positioned into a cross with each base station placed in the middle of each side of a square facing the center of the "room set-up". This reduces potential occlusions as a minimum of two base stations would be needed to detect and kinematic data from each tracker. In conclusion, VRMC technology is continuously improving, placing limitations of implementation into the manufacturing industry primarily due to software bottlenecking, with the prime example being the HTC Vive platform. Many other more current systems are available but are not supported by various DHM software for proactive ergonomics analysis. As software integrations currently exist between and ergonomics digital human modeling software, allowing for full body VRMC data to drive DHM kinematics and subsequent kinetic analyses – again allowing for more advanced and proactive physical exposure analysis (Grandi et al., 2024). Newer hardware was recently released that employs two wide-field-of-view cameras on a single tracker along with computer vision for instant spatial recognition (e.g. HTC Vive Ultimate Trackers). As VRMC technology continues to evolve, future advancements may further enhance its utility in ergonomics, expanding its applications and improving the precision of ergonomics analysis in both research and workplace settings. A brief summary of the strengths and limitations of each reviewed motion capture modality is shown below in Table 1.

Table 2.1: Summary of literature regarding motion capture systems for Digital Human Model for proactive ergonomics analysis.

<table>
<tr><th>Motion Capture Systems</th><th>Studies</th><th>Strengths</th><th>Limitations</th></tr>
<tr><td rowspan="3">Optical-Electronic Motion Capture</td><td>Merriaux et al. (2017)</td><td rowspan="3">● Sub-0.2mm positional accuracy of markers for both dynamic and static trials.</td><td rowspan="3">● High cost
● Restricted space and accessibility due to fixed camera system.</td></tr>
<tr><td>Topley & Richards (2020)</td></tr>
<tr><td>Geiselhart et al. (2016)</td></tr>
<tr><td rowspan="5">Inertial-based Motion Capture (IMU)</td><td>Roetenberg et al. (2009)</td><td rowspan="5">● Portable and can be used at non-laboratory settings.
● Relatively cost-effective
● Easy integration with VR and DHM software</td><td rowspan="5">● Inaccuracies at extreme joint angles due to drift and calculation errors.</td></tr>
<tr><td>Schepers et al. (2018)</td></tr>
<tr><td>Robert-Lachaine et al. (2017)</td></tr>
<tr><td>Walmsley et al. (2018)</td></tr>
<tr><td>Sfalcin et al. (2019)</td></tr>
<tr><td rowspan="3">HTC Vive Trackers 3.0 (VRMC)</td><td>Caserman et al. (2019)</td><td rowspan="3">● Accurate enough for visualization of body segments
● Low cost
● Easy integration with VR and DHM software</td><td rowspan="3">● Inaccurate for joint angle analysis.
● Restricted, but flexible space due to the need of at least 2 IR base stations.</td></tr>
<tr><td>Merker et al. (2023)</td></tr>
<tr><td>Vox et al. (2021)</td></tr>
</table>

	da Silva et al. (2022)	● Up to 50% operating costs can be reduced by integrating VR into DHM analysis ● Increase development and design process productivity.	● VR has been identified to be an important modality in DHM posturing but has been neglected by ⅓ of the DHM community. ● Inconsistencies between the DHM and actual movement of the human, high-setup, and lack of peripheral visual input.

2.5.4. Motion capture & VR in Ergonomics Simulations

The integration of VR and motion capture technology into current DHM software has allowed for movement simulation and body tracking in simulated environments. Previous research (e.g. Ahmed et al., 2019; Geiger et al., 2018; Geiger et al., 2020) has discussed feasibility and the importance of using these two technologies for design and ergonomics analyses. The use of motion capture systems allows tracking of human movements and postures which can be streamed into a DHM in real time to provide immersive work task simulations. By using these technologies together, ergonomics analyses can be conducted in a controlled space allowing for the identification of risks, such as extended reaching and awkward postures, during the design process. To allow for DHM recreation of human posture in VR, an important component is the ability to visualize body parts in real time. The visualization of the limbs can be achieved through the integration of motion capture and VR technologies (Servotte et al., 2020). All kinematic motion capture systems can be used as body tracking inputs depending on software capabilities of the virtual environment it is developed on. A full visualization of the user's limbs allows for a reduced distance underestimation on reaching tasks leading to more accurate movement representation of physical reality (Rizzuto et al., 2019; Gonzalez-Franco et al., 2020). Even so, out of the three systems mentioned previously (e.g. Vicon, XSens Awinda, Vive 3.0), a native VR-based motion tracking system is expected to provide the most cost-effective body tracking method (Caserman et al., 2018). The use of 6-tracker configuration has also previously been used for ergonomics risk assessments using the Rapid Upper Limb Assessment and the Rapid Entire Body Assessment (Vox et al., 2021) and is adapted for DHM body tracking in VR.

There is a current gap in the literature examining how the posturing of a DHM in VR simulations compares to the actual kinematics of the user's actual body. However, the gap to implement up-to-date VR systems into a DHM for proactive ergonomics analysis in a manufacturing context is more present than ever. For example, if the user reaches forward with their hand to a horizontal distance of 20 cm, it is unknown how much error would be present in the DHM manikin's reach. Would it underestimate the reach distance by 5 cm on average? Is the potential error consistent at different vertical or lateral locations? This information is currently lacking in the literature, which is an important limitation holding back adoption of wide-spread VR ergonomics simulations in manufacturing task analysis. Furthermore, we are uncertain as to what type of motion capture system can drive a more accurate DHM in order to conduct more accurate task analysis for proactiv ergonomics. Is an expensive, reach-grade optical motion capture system required, or does a VR-based motion capture system, at a fraction of the cost of an optical system, produce comparable errors? This thesis will attempt to address some of the above gaps in the literature.

2.6. Purpose and Hypotheses

The purpose of this research was to compare DHM-estimated ergonomics variables when their motion was driven with different optical and inertial motion capture systems in virtual reality. Two specific research questions were examined in this work:

1. What are the differences in DHM hand locations, spine compression, and joint angles when motions were driven from human models generated by inertial-, optical-, and virtual reality-based body tracking modalities?
2. How do hand location coordinates from DHM simulations compare to actual hand locations in real space when conducting virtual reality-based posture analysis?

The task was performed in Virtual Reality (VR). When compared to the actual hand locations tracked using a gold-standard kinematics, it is hypothesized that the inertial-based motion capture system and the native Vive 3.0 trackers will estimate DHM hand locations with higher RMS errors compared to the DHM hand locations from the optical system. For the means comparisons between kinematics systems, the hypotheses of this study are as follows:

H_o: There will be no significant differences observed between systems for DHM-estimated hand locations, spine compression and joint angles.

H_A: Significant differences will exist between kinematics systems as a function of varied horizontal, vertical and lateral hand positions for DHM-estimated hand locations, spine compression and joint angles.

Chapter 3 - Methodology

3.1. Participants

16 right-hand dominant adults (8 males, 8 females), with a mean age of 22.6 (2.62 σ), were recruited using a convenience sampling method from Ontario Tech University's student population. Overall, the participants had an average of 171.6 cm in height (7.72 σ), and 71.06 kg in mass (12.73 σ). This sample size was selected based on previous literature of similar nature (Godin et al., 2006; Sfalcin et al., 2019; La Delfa et al., 2021). Exclusion criteria included sensitivity to motion sickness, possible allergic reaction to adhesives, history of epileptic seizures, severe vision impairment, and any head injury within the past year. The participants were asked to provide written and verbal informed consent prior to any participation in the study previously approved by the University's Research Ethics Board #17741.

3.2. Instrumentation and Data Acquisition

3.2.1. Motion Capture

Three body tracking systems were utilized in this experimental protocol: an optical electronic motion capture system, inertial-based motion capture system, and a photosensor-based VR motion capture system. The optical system used in this study was the Vicon infrared-based system (Vicon Motion Systems, Ltd., Oxford, UK). This system, along with the use of the Vicon Nexus software, uses four Vantage cameras and six Vero cameras, each with sampling capacity of 330 Hz and a camera resolution of 2.2 megapixels. 39 infrared-reflective markers were placed on each participant following the full-body Plug-in Gait model marker template provided by Vicon as shown in *Figure 3.1,* with an additional metatarsal marker (metatarsals

1 & 5) to fit marker placement requirements from Siemens Tecnomatix to drive motion of a DHM.

The IMU system used was the Xsens MTw Awinda (Xsens Technologies BV, Enschede, The Netherlands). The system utilizes 17 IMU sensors placed by the researchers at the surface of the pelvis, sternum, upper arms (on the lateral side between the biceps and triceps muscles), forearms (on styloid process of the radius and the ulna), back of the hands, upper legs, lower legs, feet, scapula, and head. Each sensor was affixed to the participant using adhesive tape and further reinforced using Velcro straps. Kinematic data were sampled at 60Hz to ensure consistency between all systems.

The VR motion capture system used was the HTC Vive 3.0 trackers (HTC Corporation, Taoyuan City, ROC) as it was recommended by *Siemens Tecnomatix Process Simulate* for DHM integration. Six trackers were secured to the upper arms, on the torso between T1-T4, pelvis, and feet as shown on *Figure 3c,* using straps. This marker placement is provided by the *Siemens Tecnomatix Process Simulate* manual for VR tracking of the DHM[1]. The intended usage of these trackers is to track objects and body segments to facilitate full-body visualization within a VR environment. These trackers utilize both an optoelectronic system in the form of base stations emitting IR-rays into multiple photo-sensors located on each tracker, as well as an innate 9-degrees-of-freedom (DOF) inertial measurement unit containing an accelerometer and gyroscope.

[1]Siemens Tecnomatix Process Simulate Support Center: Vive Body Tracking - Hardware Requirements

Figure 3.1: Participant instrumented with a modified Vicon Full Body Plug-in Gait 39-Marker set, 17 Xsens Awinda sensors, 6-Vive 3.0 Trackers and a Vive Pro 2 head-mounted display.

3.2.2. Virtual Reality Head-Mounted Display

The HTC Vive Pro 2 (HTC Corporation, Taoyuan City, ROC) HMD was used in this experimental protocol. This model was selected as it is currently regularly used by the manufacturing industry to conduct ergonomics analyses in VR (Peruzzini et al., 2021; Hamurcu et al., 2023; Grandi et al., 2024). More specifically, the HTC Vive Pro series has been continuously explored and utilized in the literature as a research-grade immersive VR-HMD (Beese et al., 2022). The HMD is equipped with a head strap, wrist strap, and pupillary distance settings which was adjusted to each participants' anthropometrics. The HMD resolution was set to 2448x2448 pixels per eye with a 120° horizontal field-of-view at 90 frames per second (Wang et al., 2022). A room-scale calibration setup was conducted prior to the start of each session. Two HTC Vive Pro controllers were used to track and manipulate objects within the virtual environment. This setup utilizes four SteamVR Base Station 2.0 tracking systems, where multiple photo sensors located on the VR-HMD are activated based on the sweeping infrared-rays of "Lighthouses" in a 45° angle at a frequency of 90Hz. The VR environment displayed in the VR-HMD was designed in Siemens Tecnomatix Process Simulate Version 2307 (Siemens Digital Industries Software, Plano, TX, USA) with the use of the software's built-in VR Sequencer as well as AutoCAD (Autodesk, Inc, San Francisco, CA, USA).

3.3. Experimental Procedure and Protocol

3.3.1. Experimental Design

This experimental design followed a repeated measure randomized control study design where participants performed an object grasping and placement task in VR while instrumented with all the motion capture sensors to assess the accuracy of each system. The order of table heights were randomized to mitigate carry-over effects.

3.3.2. Experimental Set-Up

In the VR environment, participants stood in front of a table at one of the three heights: 62.5 centimeters, 95.3 centimeters, and 128.0 centimeters. These three table heights were fixed across all participants, as manufacturing workstations are generally set at a fixed height and are used to simulate common vertical distances within a workplace's reach envelope. There were nine target locations on the surface of the table marked with a numerical order number from the top left-hand side of the participant created using the VR sequencer function in *Siemens Tecnomatix Process Simulate*. There were three locations in each row: left and right lateral locations and a center location - each 31.1 cm away between columns and 15 cm between rows. An interactable cylindrical object was present on the table. It had to be grasped by the participant, then moved to each target in a specified order as shown in *Figure 3.2*.

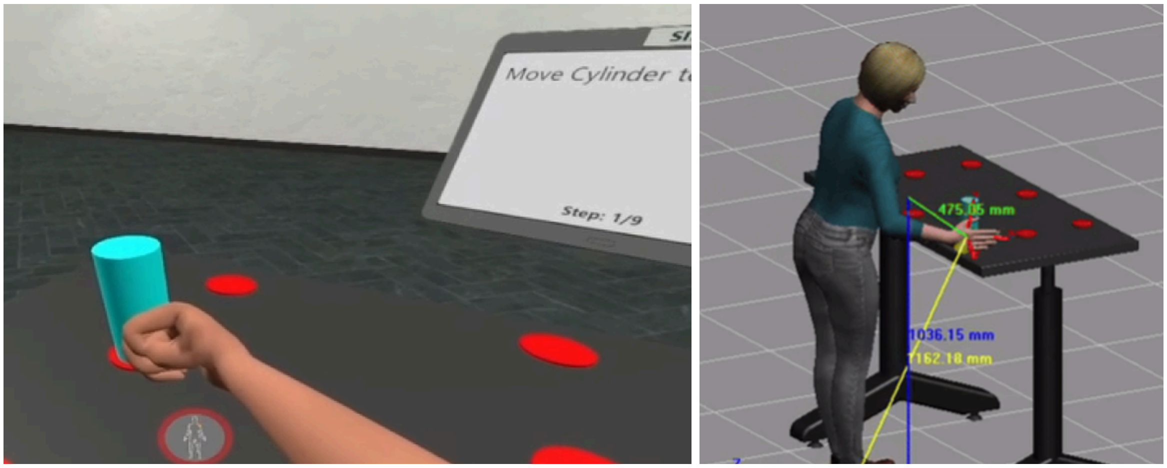

Figure 3.2. *Left:* Participant's point-of-view in VR of the 3D table during completion of the task. *Right:* Scene-view of the participant completing the task.

3.3.3. Experimental Protocol

After the participant provided verbal and written consent, they were briefed on the timeline of the protocol, controls in VR, as well as the calibration process. Participant height, mass, foot length, shoulder height, shoulder width, elbow, wrist span, arm span, hip height, hip width, knee height, ankle height, head breadth, head length, chest circumference, waist circumference, waist circumference, arm length, elbow-to-wrist length, hand length, hand breadth, hand depth, and foot breadth are then measured. Each participant's anthropometrics were collected to create their anthropometrically-scaled DHM (i.e. digital twin) as well as inputs for motion capture modelling. Afterwards, the participant was instrumented with the 39-passive retro-reflective markers, the 17 Xsens sensors, and the 6 Vive 3.0 trackers. Once fully-instrumented, the participant conducted the calibration processes for each system, guided by the researcher following the process outlined in each system's respective user manual. After the participant was properly oriented with the HMD, they performed the object placement task in VR in a block randomized order for table height. After the conclusion of all tasks, sensors were removed from the participant before they filled out the UX-IVE Questionnaire. *Figure 3.3* indicates a timeline summary of how the experimental protocol was implemented. This marks the end of the proposed experimental protocol.

Figure 3.3. Experimental Protocol in chronological order, including the flow of data into the DHM.

3.4. Data Processing and Analysis

All kinematics data were streamed into Siemens Tecnomatix Process Simulate (TX, USA), a manufacturing process design software. All collected motion data from all participants were used as an input into Process Simulate to drive kinematics of the participant-scaled DHM. Motion data from the HTC Vive Trackers were directly recorded during the trial through the "Posture Recorder" function into a task simulation file through the "Task Simulation Builder" function. After the collection period for each participant, IMU data from the Xsens MVN Analyze software was processed using the "HD Reprocess" function before being streamed into *Process Simulate* and recorded through the "Posture Recorder" function in *Process Simulate*'s "Task Simulation Builder" function. Kinematic data from the IMU were matched to the DHM using the "match hand location"option, where DHM would match hand locations from the IMU data and would then estimate joint angles and poses to reach that point. As for the optical motion data, reconstructed trials were visually analyzed for proper marker trajectories and labels. Gaps in trajectories were filled using the rigid body fill option when applicable. Gaps of 5 or less frames were filled using a Woltring spline. Other gaps that did not fit into those criteria were filled using the pattern fill option using the closest matching trajectory. Marker trajectory data were then filtered in Vicon Nexus using a dual-pass, low-pass digital fourth order Butterworth filter with a frequency cutoff of 6Hz before exported into a .c3d file. This file is then imported into the motion capture player in Process Simulate and recorded using the "Posture Recorder" into a task simulation file. From this, using the Task Analysis Toolkit (TAT) for each task simulation file, a time history of hand location joint centers, joint angles, and spine compression were computed. These outputs are generated in the form of an extensible markup language (XML) file, where further data processing and cleaning were conducted in R.

Using the time-series joint center data output from the DHM manikin, custom code was created in LabView (v2020, National Instruments, Austin, Texas) to calculate hand locations relative to a point on the DHM manikin, so comparisons could be made to actual position data from markers on the participant. To achieve this, horizontal displacement (H), vertical displacement (V) and lateral displacement (L) were calculated from the middle knuckle to the midpoint of the ankles, as this is a common convention to define hand location in ergonomics DHM analyses. These same H, V and L displacements were also then computed for the Vicon marker coordinate data from the middle knuckle and midpoint of the angles, such that a comparison of DHM to true H, V and L displacements could be conducted using the same local coordinate system with the origin defined between the ankles. Both the DHM-based H, V and L, as well as the ground truth H, V and L, were calculated from a 0.5 second average window length from the time-series signals when the participant placed the bottle on each of the targets. These instances were visually identified in Labview based on hand velocities near zero when the participant held the bottle on the target. The flow of data processing is shown in *Figure 3.4*.

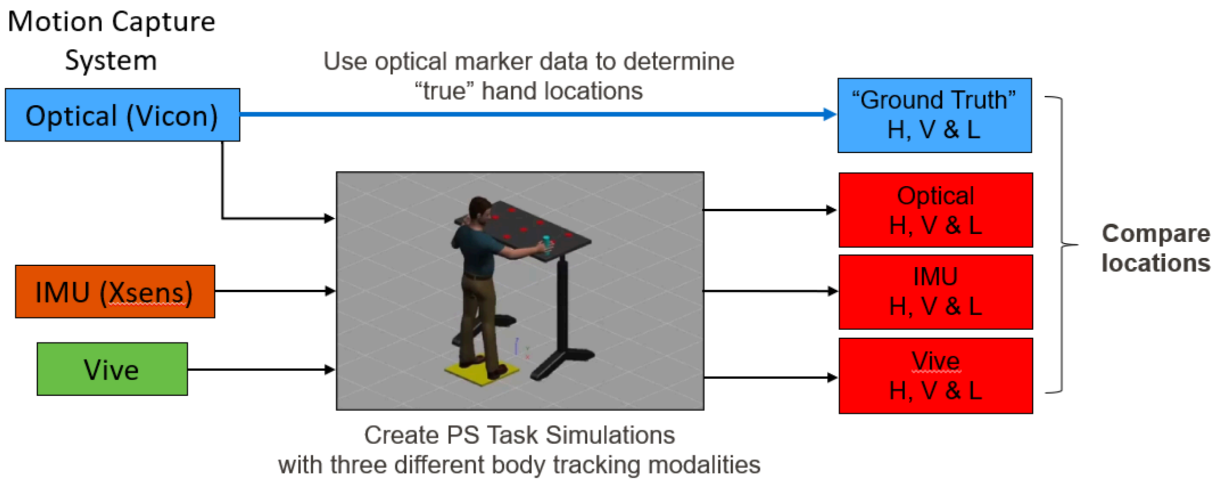

Figure 3.4: The flow of motion capture data from collection, to DHM, to dependent variable outputs.

3.5. Statistical Analysis

All experimental conditions were compared between factors to investigate the differences between each body tracking method for the ergonomics parameters of interest (hand locations, spine compression and joint angles). Root mean square errors (RMSE) were calculated to examine the overall accuracy of the DHM-hand locations compared to the actual location of the participants' hand. Furthermore, hand displacement, trunk flexion angle, shoulder elevation angle (relative to gravity), elbow flexion angle and spinal compression were considered in separate three-way mixed effects models using a 95% confidence interval ($p<0.05$). A Type III Analysis of Variance (ANOVA) was conducted to examine the effects of vertical target location, horizontal target location, lateral target location, and systems on the dependent variables. Afterwards, Tukey's post-hoc pairwise comparison analysis was conducted to explore extraneous and interaction effects between systems at each significant target location. A Bland-Altman analysis was also conducted for all systems paired with the actual location to determine levels of agreement at the horizontal, vertical, and lateral hand displacements following the system variables. Statistical analyses of this study were performed using RStudio statistical software (Posit, PBC., Boston, MA, USA).

Chapter 4 - Results

4.1. Root Mean Square Error of Hand Location

Overall average DHM hand locations showed an RMSE of greater than 10 cm, compared to actual hand locations, across all systems assessed. Hand locations tracked using Vive showed the lowest overall RMSE relative to actual hand locations by 13.7 cm. The IMU system had the highest RMSE at an overall error of 24.3 cm (*figure 4.1*). Additionally, Vive was found to have an 8 cm RMSE for horizontal hand location when compared to the raw kinematics data. The IMU system shows the highest RMSE at 32.8 cm for the furthest horizontal reach at the medium table height.

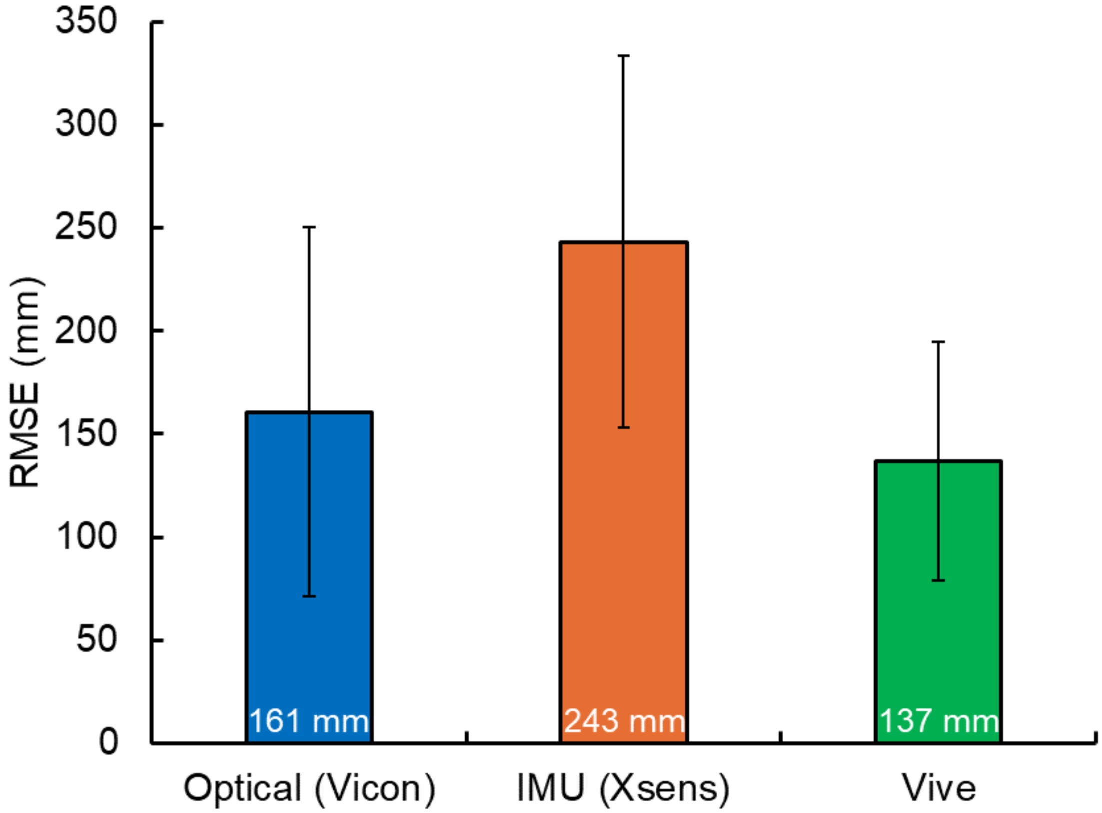

Figure 4.1: Overall hand location RMS error (averaged H, V and L) for DHM outputs between Optical, IMU, and Vive system inputs.

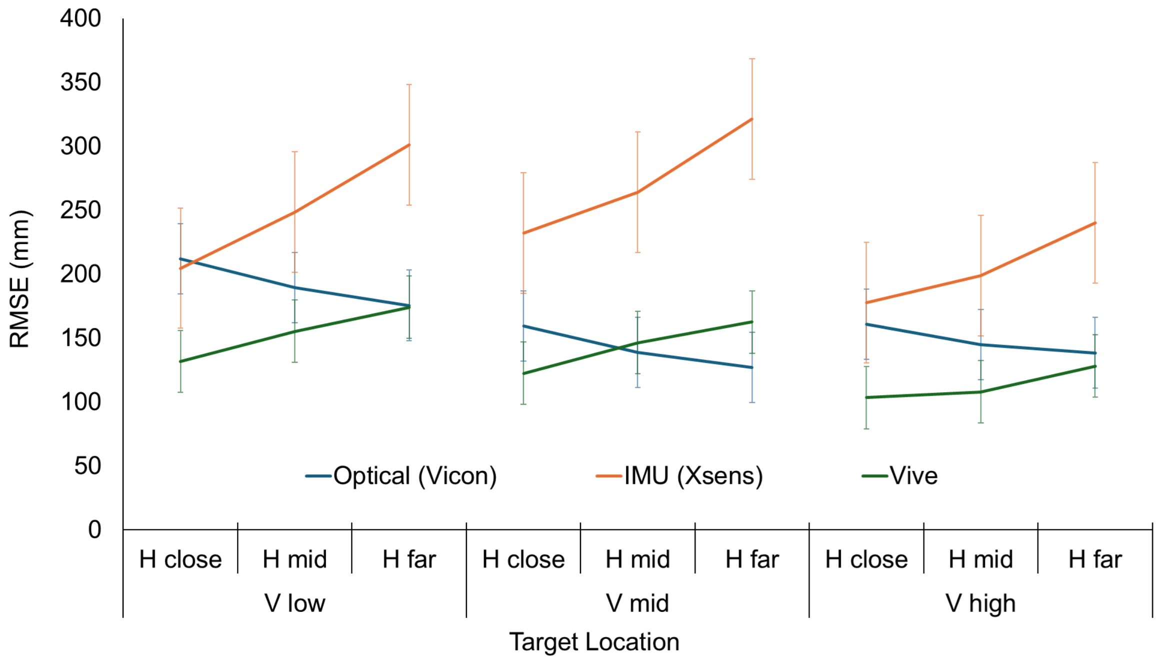

Figure 4.2: Overall RMS error separated by vertical and horizontal location of target between each of the systems.

4.2. Mixed Effects Models for Hand Locations

4.2.1. Horizontal Displacement (H)

A three-way interaction among vertical target location, horizontal target location, and system was found to be significant (F = 90.9, p = < 0.001), suggesting that a combined influence of the vertical target location and horizontal target location varied significantly by system ($\eta 2$ = 0.89). Errors in horizontal distance hand locations can further be seen in *figure 4.3* in which larger Xsens IMU system shows errors of up to 25.8 cm below the actual location at the lowest table height setting.

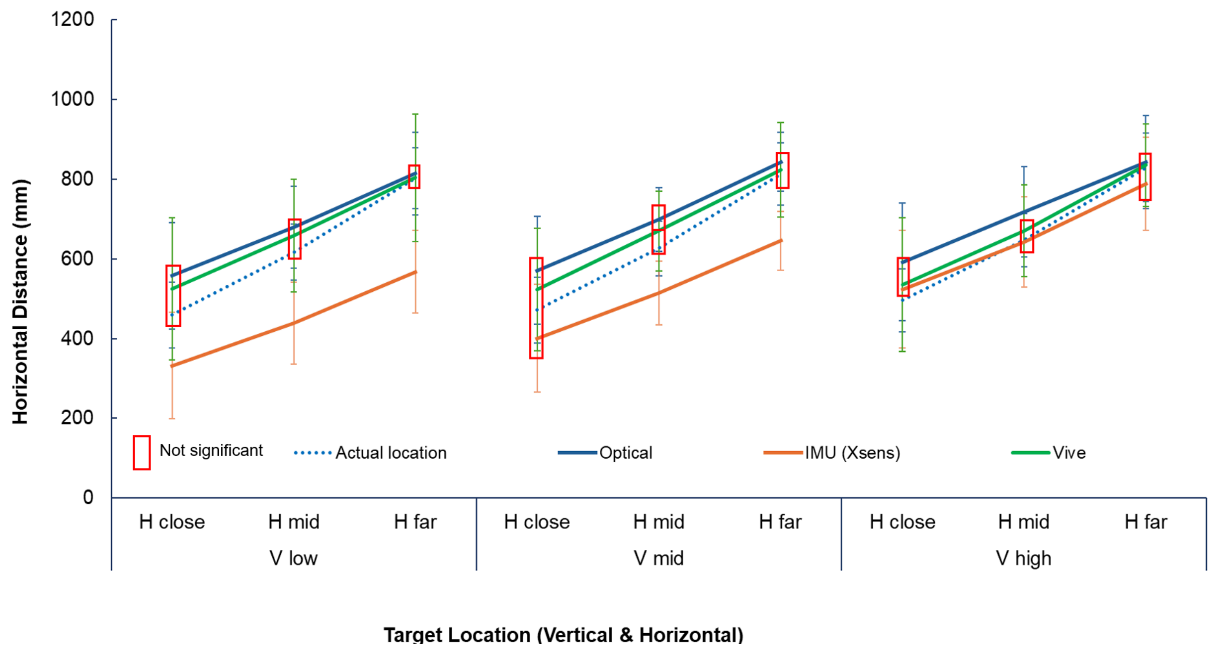

Figure 4.3: Horizontal distances of DHM hand locations across horizontal target locations and vertical target locations between systems. The dotted line represents actual measured H distances locations. Due to the high number of significant pairwise comparisons (see *Table 1* in Appendix B), means encapsulated within a red box indicate a non-significant difference. Any means between the systems that are not within a red box are significantly different from the other means.

Tukey's Honestly Significant Difference Pairwise comparisons between motion capture systems across various levels of horizontal target locations (categorized as Close, Mid, and Far) and vertical target locations (categorized as Low, Mid, and High) showed several significant differences in the interactions as shown on *Table 1* in *Appendix B*. It is important to note the highest mean difference of 31.9 centimeters between the actual location and IMU occurs at the low and far target location. Similarly, higher differences tend to occur in the low vertical target locations, such as 33.0 cm between the Optical and IMU pairing.

Agreement analyses between systems and actual location were conducted using Bland Altman plots. The mean difference for VRMC was 12 millimeters, which was the closest to 0 when compared to other systems (*figure 4.3*), indicating that the Vive system was most similar to the actual H displacement. At H values below 700 millimeters in the IMU (*figure 4.5*) and Vive (*figure 4.6*) systems, funneling past the upper limit (i.e. heteroscedasticity) occurs. Overall mean difference was greatest in the IMU system at 163 millimeters greater than 0 with wider 95% limits of agreement at -400 millimetres to 400 millimetres, indicating higher variability in the spread of the data points. The IMU system appears to have a pattern in the distribution of data points, where at lower averages, the differences appear more scattered with errors approaching 800 mm. However, as the average hand location values increase, the differences become more clustered around zero. The optical system comparison shows a slight increase in differences as the average hand location values increase, but with no significant widening of spread as averages increase (*figure 4.4*).

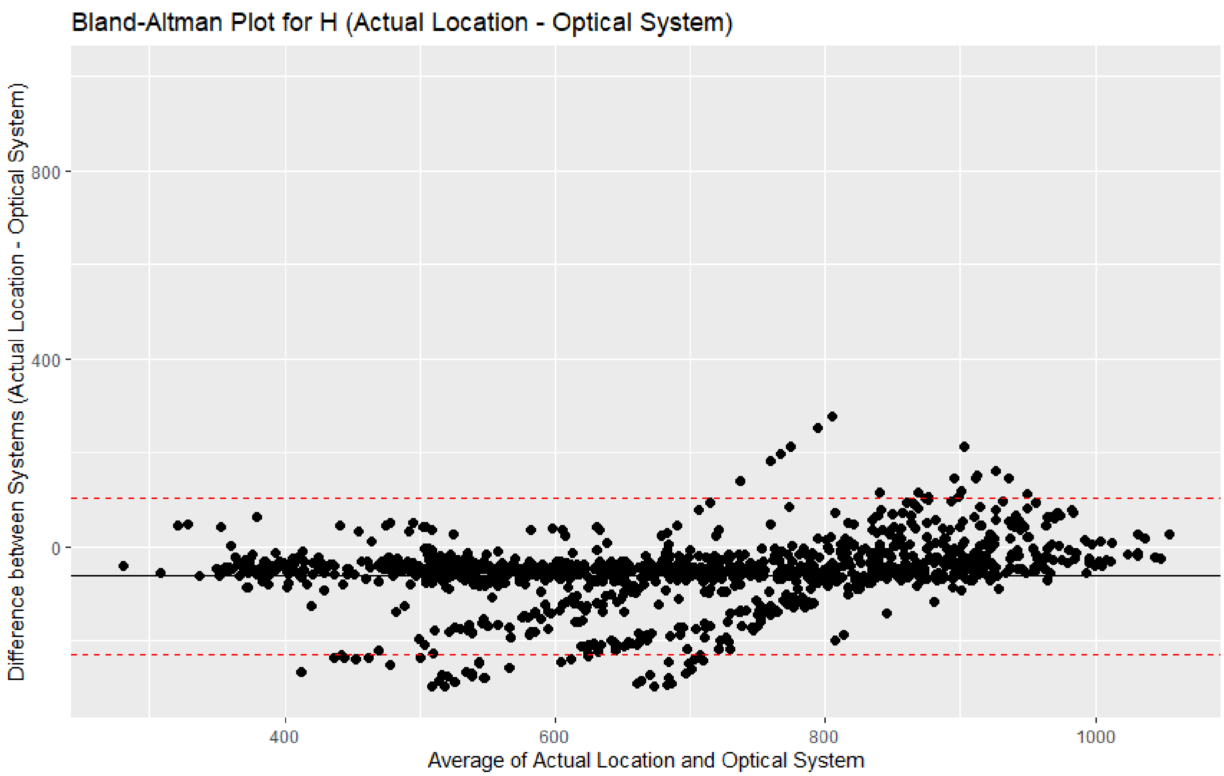

Figure 4.4: Bland-Altman plot of horizontal hand distance agreement between actual locations and Optical (Vicon) system.

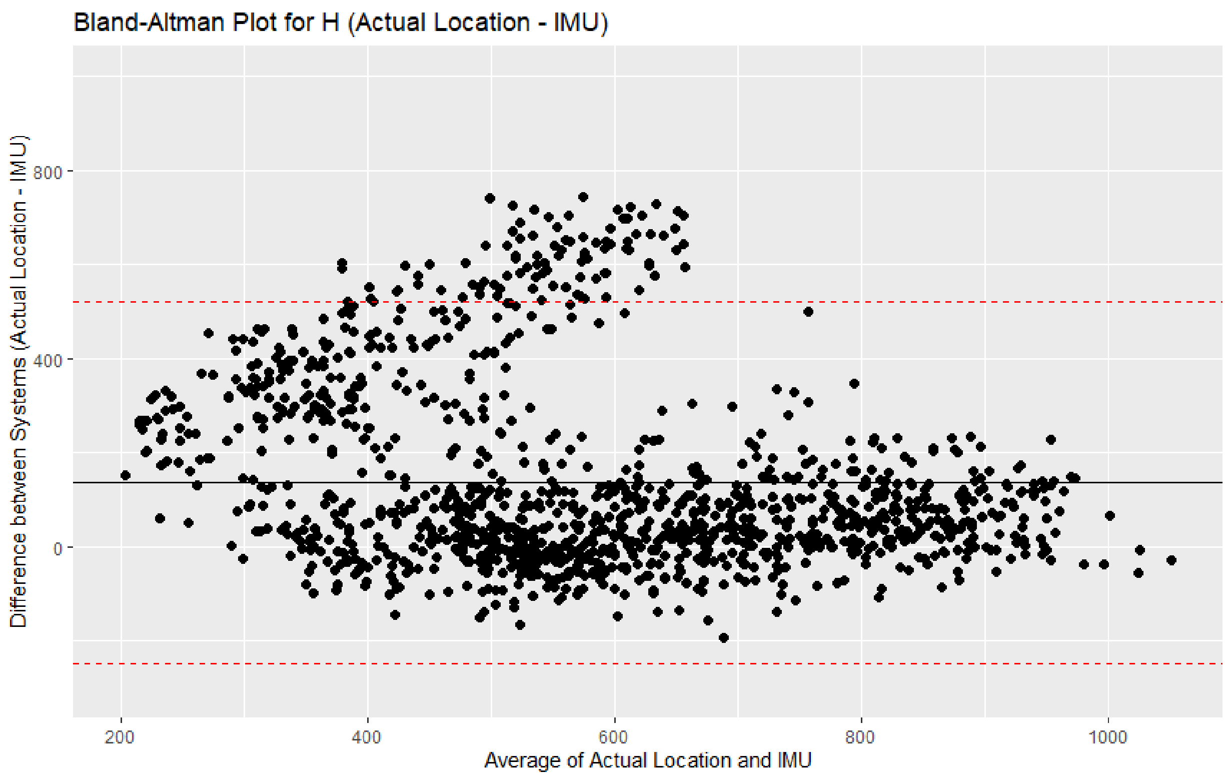

Figure 4.5: Bland-Altman plot horizontal hand distance agreement between actual locations and IMU (Xsens) system.

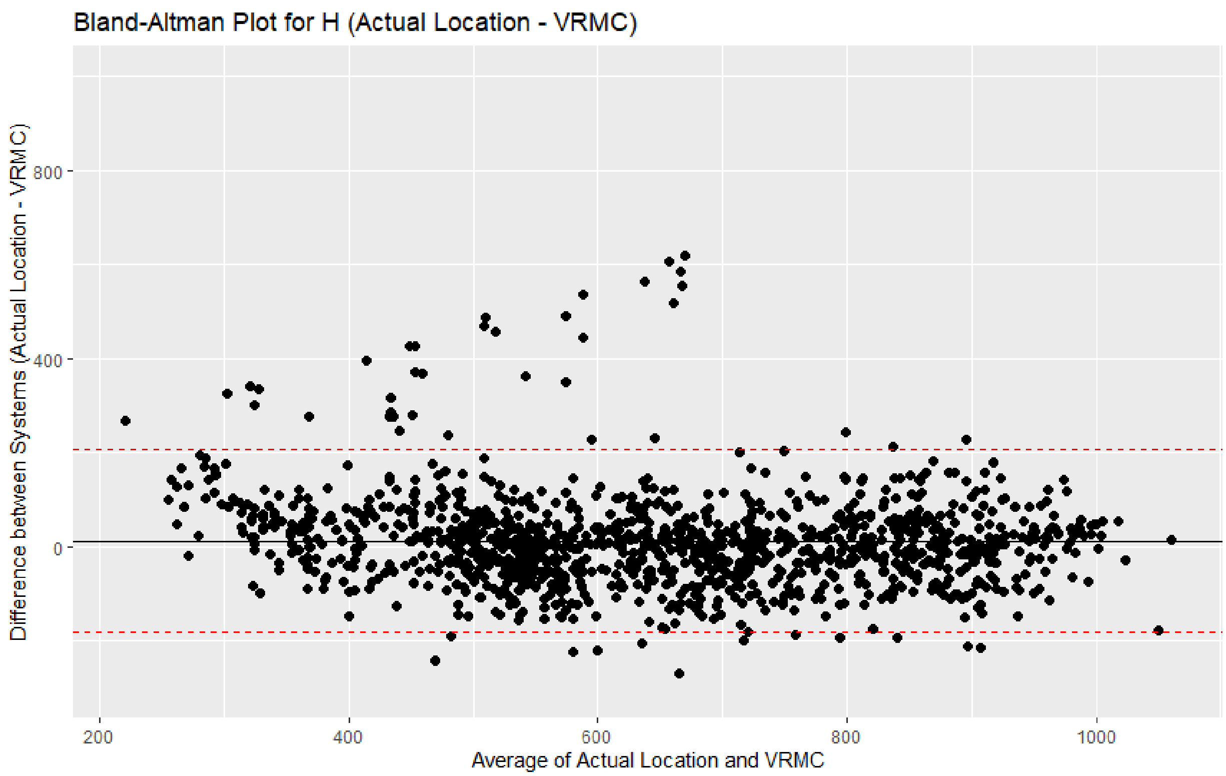

Figure 4.6: Bland-Altman plot of horizontal hand distance agreement between actual locations and VRMC (Vive) system.

4.2.2. Vertical Displacement (V)

A significant interaction of vertical target location and system was found for vertical hand displacement ($F_{(8, 6199.2)} = 144.46$, $p < 2.2e\text{-}16$, $\eta 2 = 0.16$), indicating that the means of vertical target location varied by system. Similarly, horizontal target location also significantly influenced the vertical hand location, $F_{(2, 6198.0)} = 5.20$, $p = 0.005514$, $\eta 2 = 1.68e\text{-}03$. Another significant interaction was found between horizontal target locations and systems ($F_{(8, 6198.0)} = 2.20$, $p = 0.024682$, $\eta 2 = 2.83e\text{-}03$). IMU errors suggest an underprediction of vertical hand location at all target height by an average of 20.26 cm across all vertical target locations as shown on *figure 4.7*. The remaining interactions, including higher-order interactions, did not reach statistical significance based on p-values exceeding 0.05.

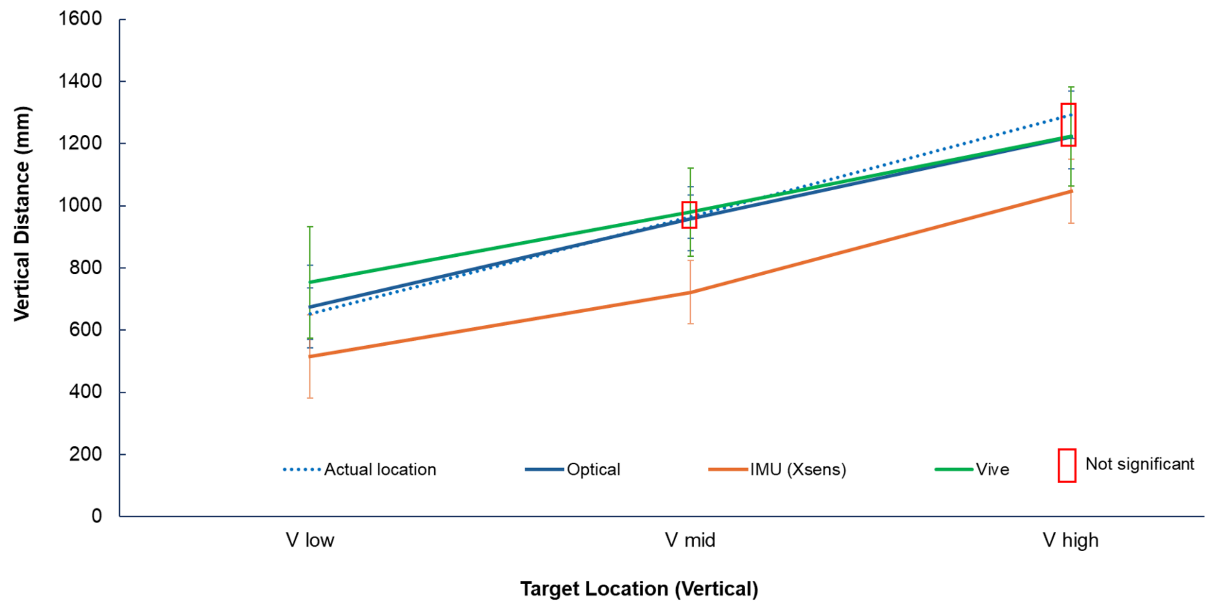

Figure 4.7: Vertical distances of DHM hand locations across vertical target locations between systems. The dotted line represents actual measured V distances locations. Due to the high number of significant pairwise comparisons (see Table 2 of Appendix B), means encapsulated within a red box indicate a non-significant difference. Any means between the systems that are not within a red box are significantly different from the other means.

Pairwise comparisons between motion capture systems were conducted to measure the interaction effects between systems at various vertical target locations on the outcome measure vertical hand location as shown in *Table 2* of *Appendix B*. Like horizontal hand location values, IMU's mean differences are greater when compared to all the other systems at a minimum difference of 173 millimeters, suggesting there are greater deviations involving IMU values. Vive had the lowest difference between the three systems at all vertical target locations, with a 116.35 millimeter mean difference at the low vertical target location.

The mean difference of Vive was at 87 mm from zero, suggesting minimal overall bias between the actual location and Vive system. The data points are clustered into distinct groups along the x-axis with outliers present above 500 millimeters. The IMU mean difference was +249 millimeters greater than zero. Consistent positive bias suggests that

IMU measurements were underestimated by 249 millimeters compared to the actual vertical target location. Compared to Vive and optical system mean differences, the IMU mean differences are significantly different. The appearance of data “clusters” are present because of the spacing in between the three vertical target locations. There were however, larger clusters of errors below the -250 mm.

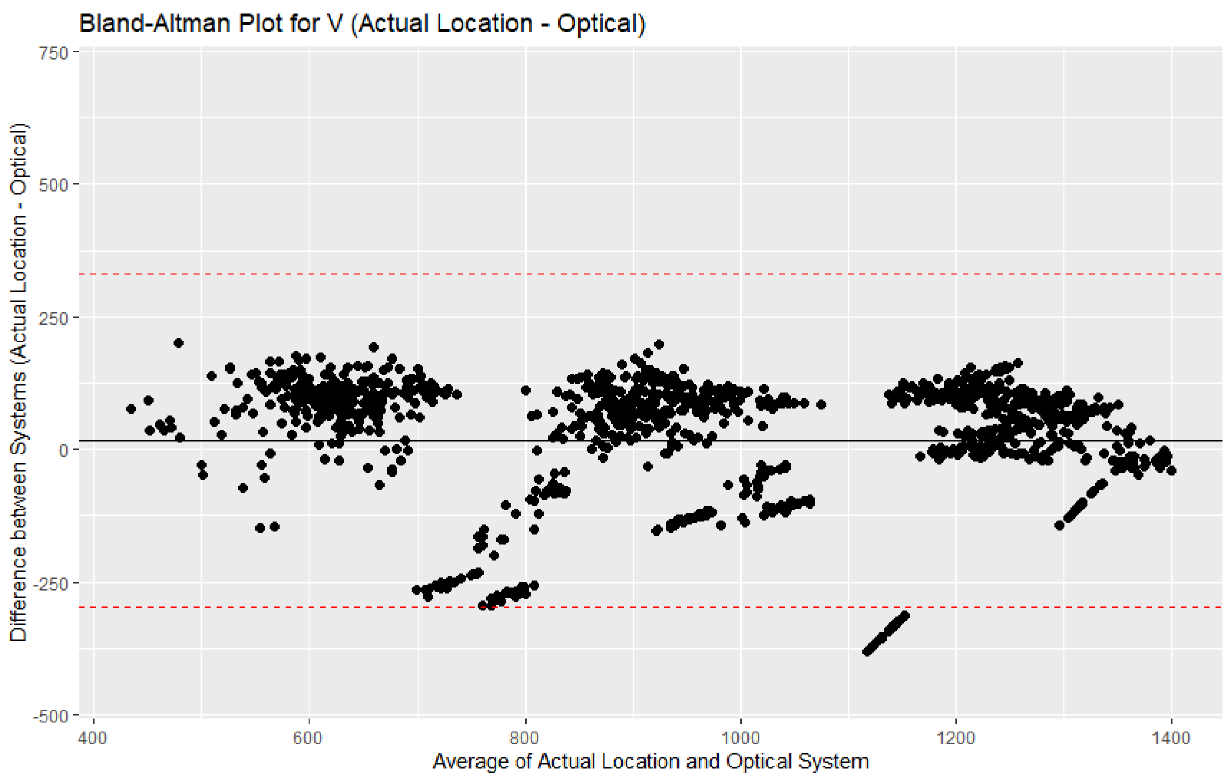

Figure 4.8: Bland-Altman of vertical hand distance agreement between actual locations and Optical (Vicon) system.

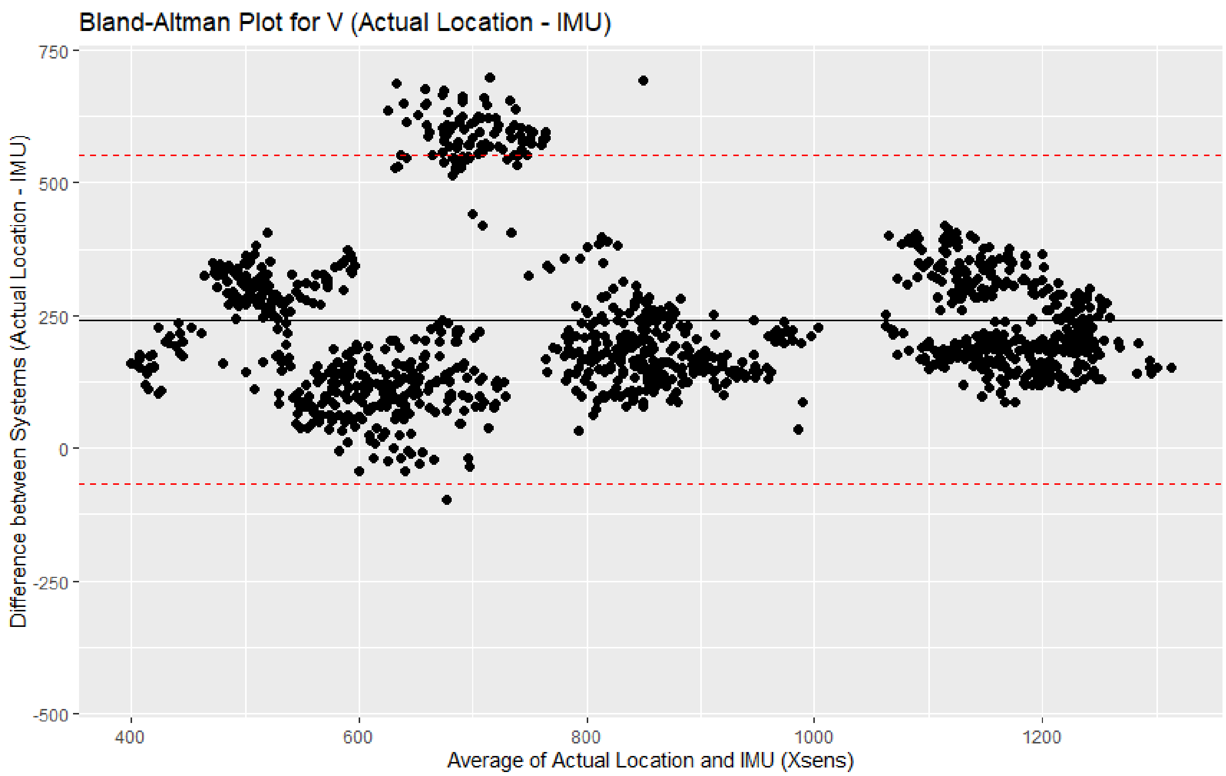

Figure 4.9: Bland-Altman of vertical hand distance agreement between actual locations and IMU (Xsens) system.

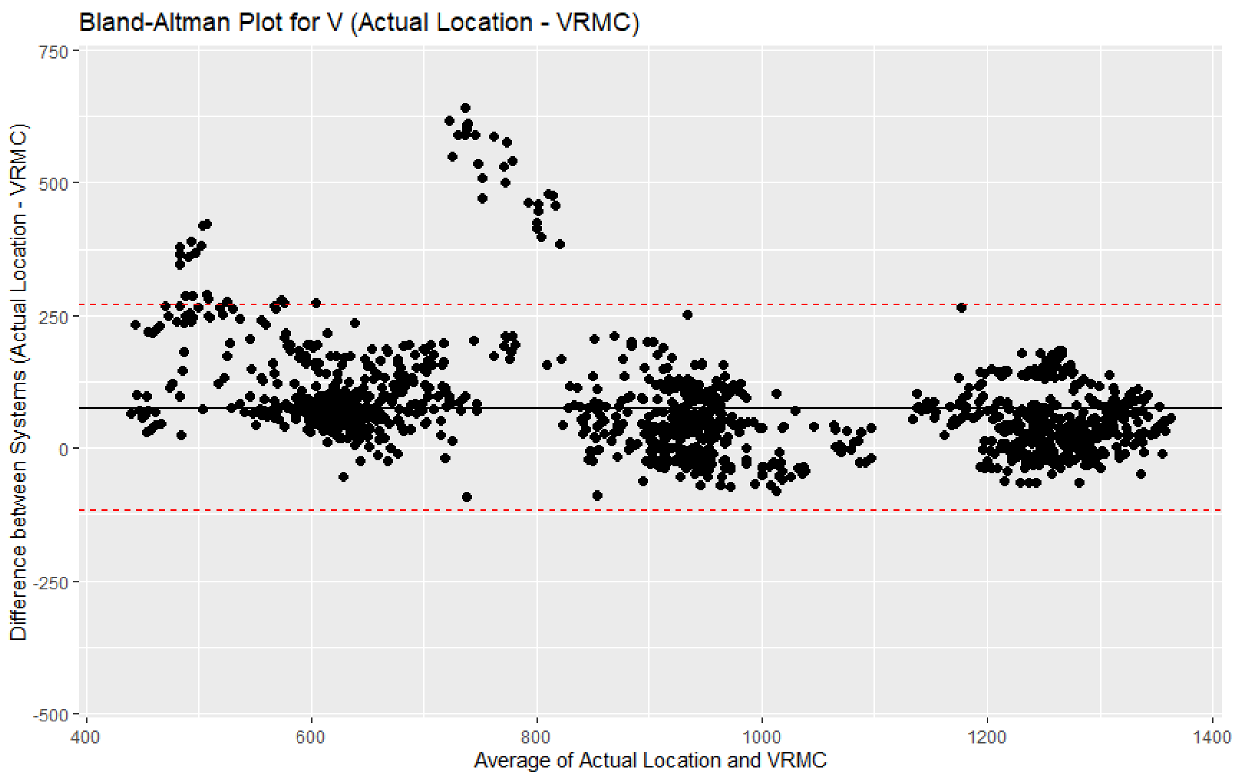

Figure 4.10. Bland-Altman of vertical hand locations agreement between actual locations and VRMC system.

4.2.3. Lateral Displacement (L)

The results of an ANOVA for lateral hand locations indicated a significant effect of vertical target location, lateral target location, and systems on lateral displacement of the hand ($F_{(16, 6196.1)} = 4.3249$, $p < 0.001$, $\eta 2 = 0.01$), indicating that lateral displacement varied by system, height, and lateral target location. Similarly, the interaction between horizontal target location and systems significantly influenced the lateral displacement ($F_{(8, 6196.1)} = 5.7081$, $p < 0.001$, $\eta 2 = 7.32e\text{-}03$). Pairwise comparisons between motion capture systems were examined as a function of vertical target locations and lateral target locations (Figure 4.11, *Table 3* in *Appendix B*). Vive showed distinct mean differences compared to other systems. At all vertical target locations, Vive showed a positive mean difference, with the greatest difference being 156.05 millimeters. The other systems had negative mean differences at left and middle lateral target locations, with the IMU system showing the greatest mean difference of positive 274 millimeters at the right lateral target location.

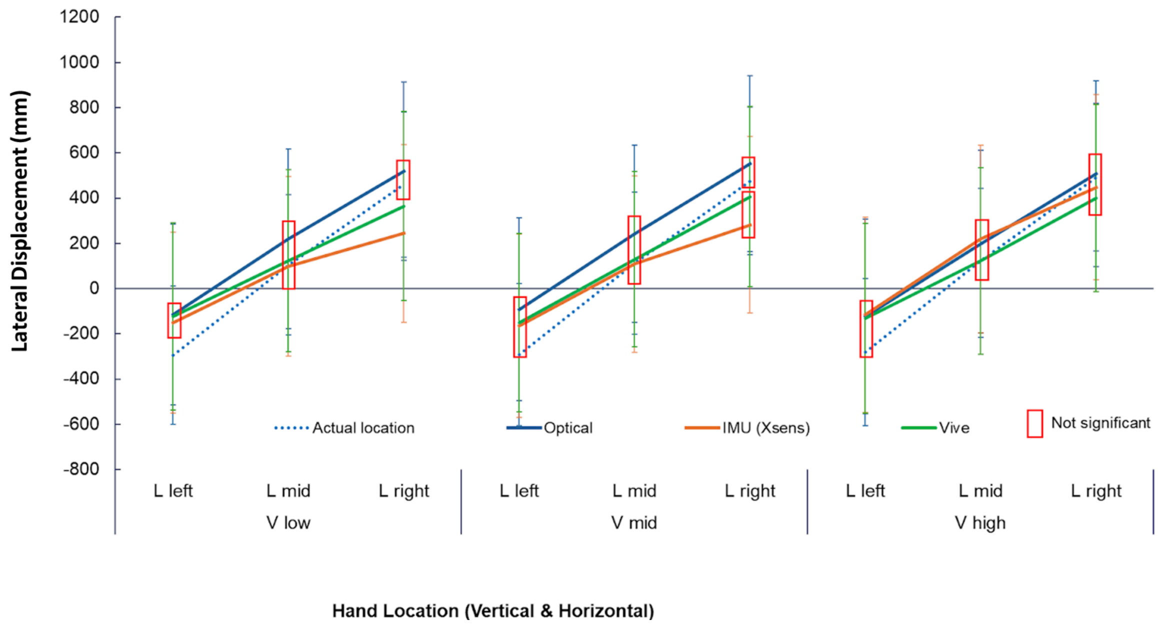

Figure 4.11: Lateral distances of DHM hand locations across lateral target locations and vertical target locations between systems. The dotted line represents actual measured L distances locations. Due to the high number of significant pairwise comparisons (see Table 3 of Appendix B), means encapsulated within a red box indicate a non-significant difference. Any means between the systems that are not within a red box are significantly different from the other means.

Bland-Altman plots for lateral hand locations indicate a consistent mean difference across all systems near zero. Lateral displacements of optical and VRMC systems mostly fall within their limits of agreements of -450 to 350, and -200 to 450, respectively. Optical values were scattered near zero differences but several outliers were present which caused the mean difference to be of lower value. The mean difference for IMU is less than 100 millimeters and had limits of agreement between the -450 and +500 millimeters, suggesting some variability but a close mean agreement. The lateral hand location points are spread around the mean difference with some clustering at various target locations. There is a slight upward trend at average values greater than 250 millimeters indicating that differences may increase at higher average values.

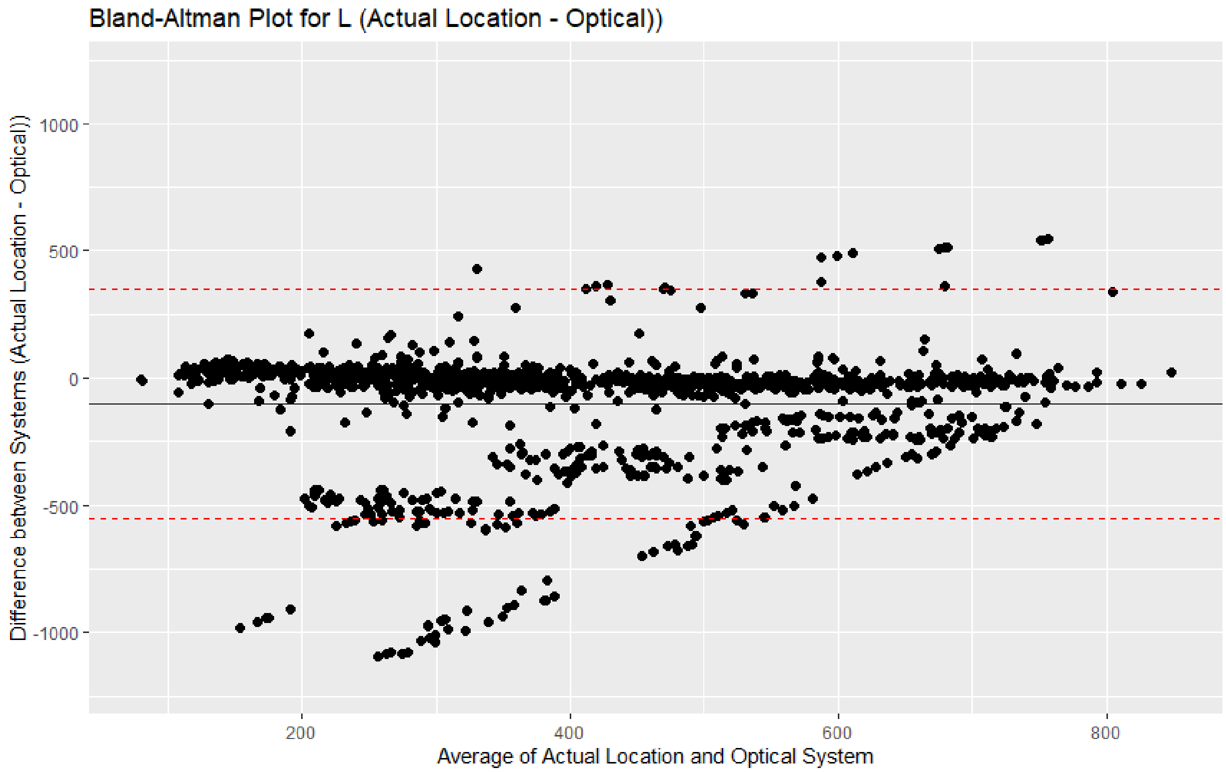

Figure 4.12: Bland-Altman of lateral hand distance agreement between actual locations and Optical (Vicon) system.

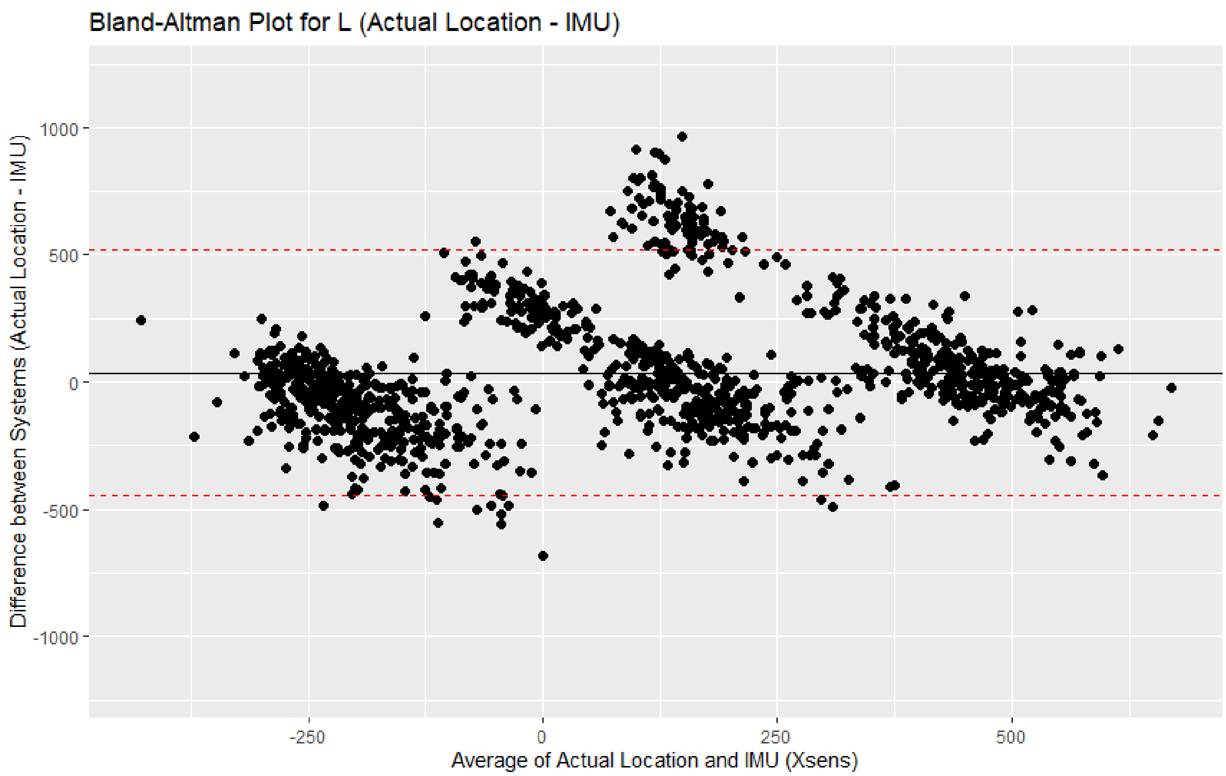

Figure 4.13: Bland-Altman plot of lateral hand distance agreement between actual locations and IMU (Xsens) system.

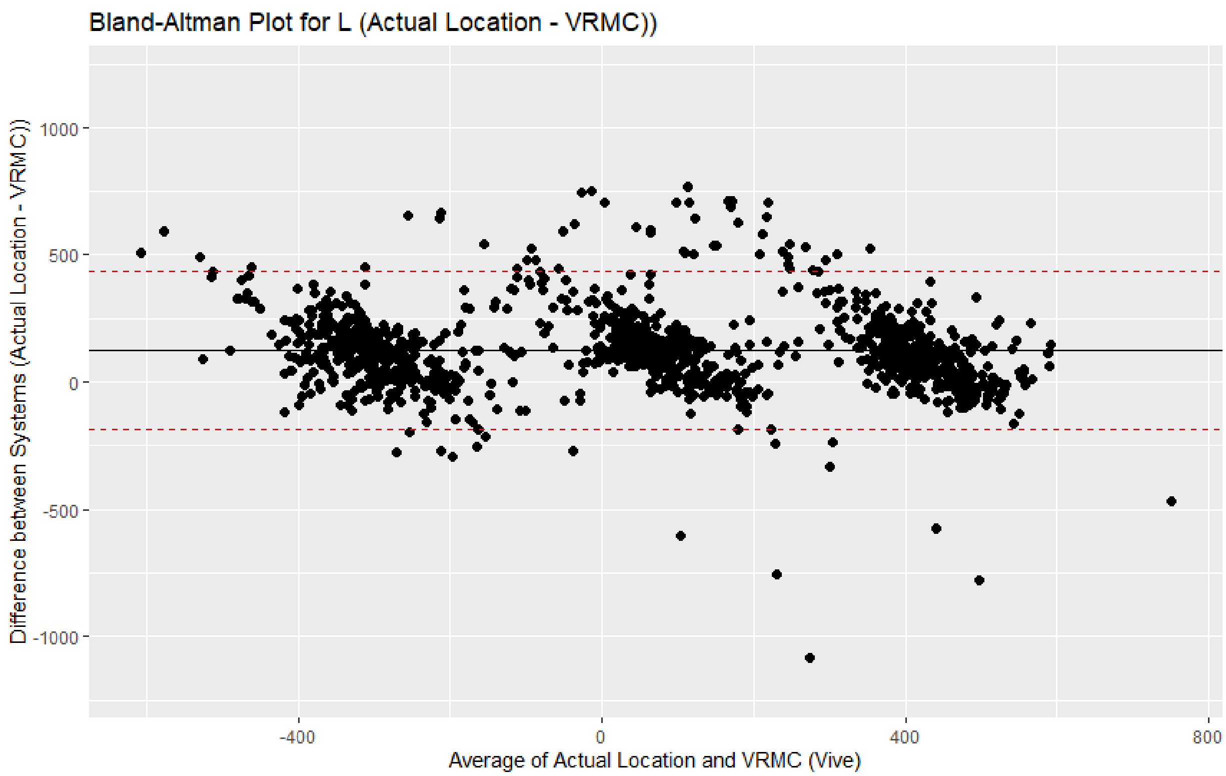

Figure 4.14. Bland-Altman plot of lateral hand distance agreement between actual locations and VRMC system.

4.2.4. Spine Compression

Significant interaction effects were observed in spine compression involving the motion capture systems and vertical target location ($F= 52.3$, $p < 0.001$, $\eta 2 = 0.06$), systems and lateral target location ($F = 4.36$, $p < 0.001$), vertical target location and horizontal target location ($F = 53.6$, $p < 0.001$), vertical target location and lateral location ($F = 7.64$, $p <0.001$). Pairwise comparisons of systems at each vertical target location was conducted, with the highest mean difference between Vive and IMU at 575.23N on the low vertical target location.

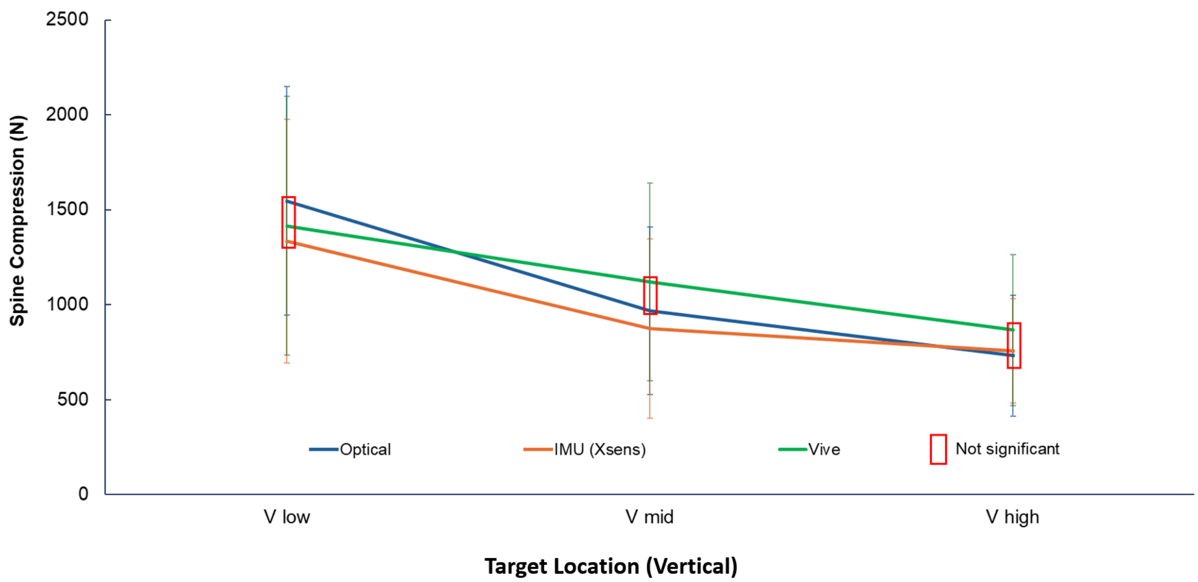

Figure 4.15: Spine compression of the DHM across vertical target locations between systems. Due to the high number of significant pairwise comparisons (see Table 4 of Appendix B), means encapsulated within a red box indicate a non-significant difference. Any means between the systems that are not within a red box are significantly different from the other means.

4.2.5. Joint Angles

4.2.5.1. Trunk Flexion

Significant interaction effects were observed in trunk flexion angle at a three-way interaction between the motion capture systems, horizontal target location, and vertical target location

(F= 4.49, p = 0.008581, η2 = 0.01). The three-way interaction of horizontal target location, lateral target location, and systems was also significant (F = 2.09, p = 0.0147, η2 = 7.40e-04). Vive showed a different trend as opposed to the other systems at the lateral target locations with the right target always at a lower angle regardless of horizontal target location as shown in *figure 4.16*. Pairwise comparisons of systems for joint angle indicates an increased flexion angle difference between the IMU and VRMC pairs with an angle difference of around 15 degrees.

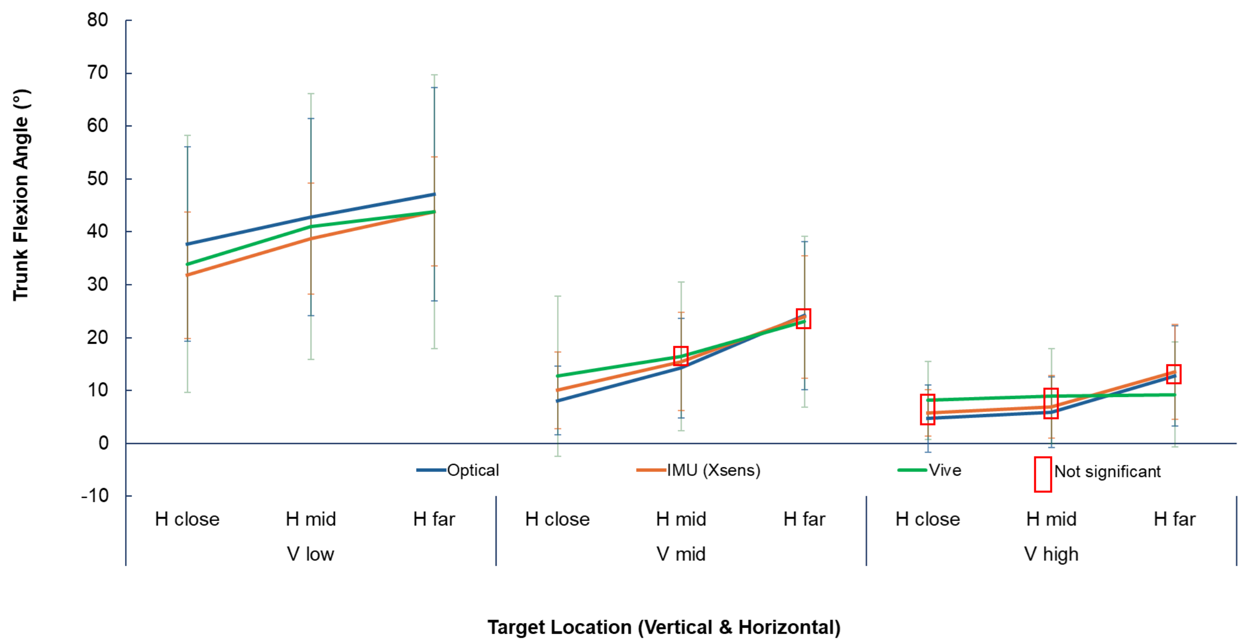

Figure 4.16: Trunk flexion angle of DHM across horizontal target locations and vertical target locations between systems. The dotted line represents actual measured H distances locations. Due to the high number of significant pairwise comparisons (see Table 5 of Appendix B), means encapsulated within a red box indicate a non-significant difference. Any means between the systems that are not within a red box are significantly different from the other means.

4.2.5.2. Right Shoulder Flexion

A three-way interaction for right shoulder flexion angle involving the motion capture systems, vertical target location, and horizontal target location ($F = 5.811$, $p < 0.001$, $\eta2 = 0.01$) was found to be significant. Systems and lateral target location ($F = 3.143$, $p = 0.004465$, $\eta2 = 3.77e\text{-}03$) means were also significant. All systems stayed consistent in flexion angle as horizontal target location increases. Pairwise comparisons of systems indicate a mean difference between all significant pairs to be less than 25 degrees except for the Vive-IMU pair at low vertical target location and far horizontal target location (see *Table 6* of *Appendix B*).

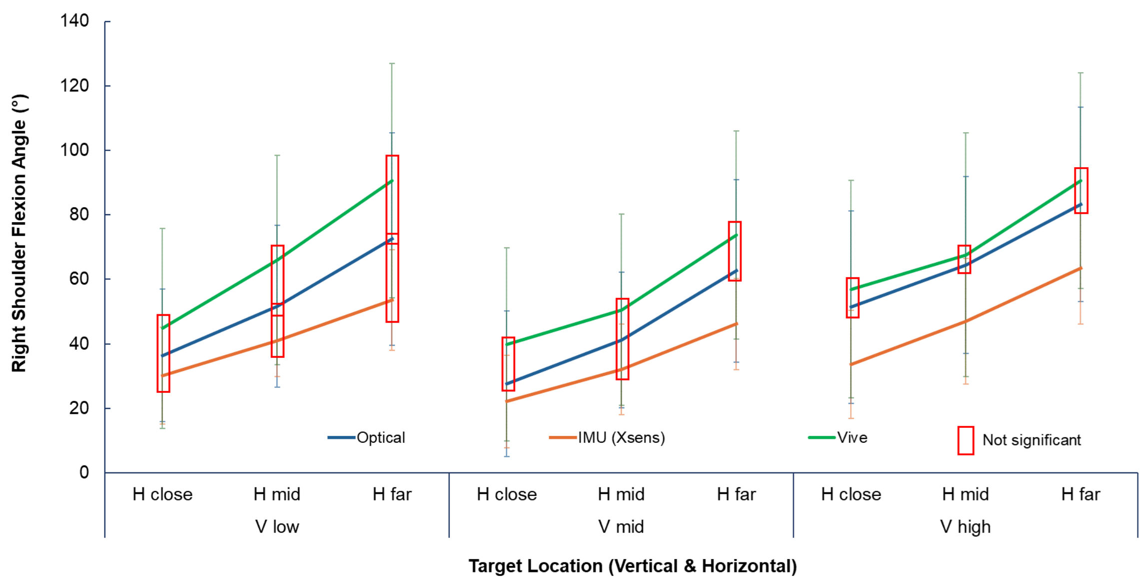

Figure 4.17: Right shoulder flexion angles across vertical target locations and horizontal target locations between systems. Boxed values represent not significant pairs (see Table 6 of Appendix B).

4.2.5.3. Elbow Flexion

A three-way interaction for right elbow flexion angle involving the motion capture systems, lateral target location, and horizontal target location ($F = 2.044$, $p = 0.0174$, $\eta 2 = 4.75e-03$) was found to be significant. Systems and vertical target location ($F = 17.73$, $p < 0.001$, $\eta 2 = 0.02$) means were also significant. Pairwise comparisons of systems indicate a mean difference between all significant pairs to be less than 25 degrees except for the Vive-IMU pair at mid vertical target location and close horizontal target location (see *Table 7* of *Appendix B*).

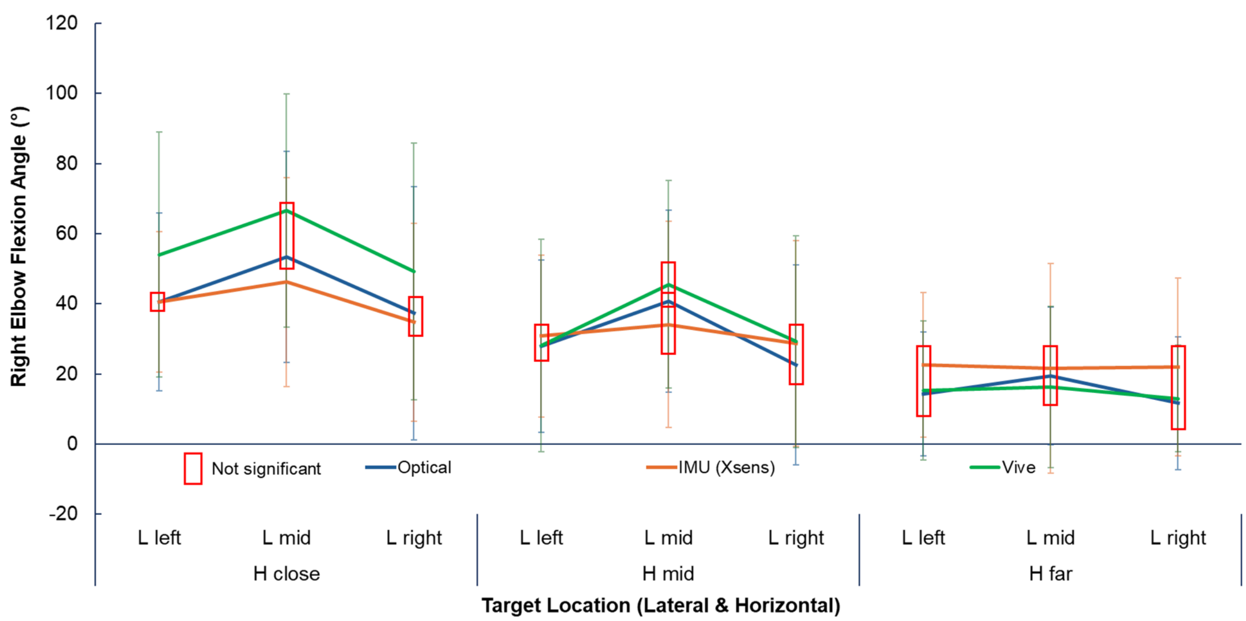

Figure 4.18: Right elbow flexion angles across lateral target locations and horizontal target locations between systems. Boxed values represent not significant pairs (see Table 7 of Appendix B).

Chapter 5 - General Discussion & Conclusions

5.1. Discussion

In this study, participants completed a reaching task across nine targets at three different vertical locations, while instrumented with three different motion capture systems, to determine the accuracy of VR-based body tracking modalities. The task was conducted in VR with the use of a hand-held controller. Kinematics inputs form the three motion capture systems (Optical, Xsens and Vive) were used to create DHM manikins scaled to the anthropometrics of each participant, from which the hand locations, joint angles and spine compression of the DHM could be compared between systems, and also against actual (i.e. ground truth) hand location data measured using gold-standard optical kinematics. These dependent variables (i.e. H, V, L, spine compression, shoulder and elbow flexion angles) were evaluated as a function of motion capture system, horizontal, vertical and lateral location of the targets (independent variables). As such, the primary purpose of this study was to investigate the differences and accuracy between IMU, optical, and VR-based body tracking as inputs for ergonomics analyses using a DHM. It was hypothesized that the Optical system DHM to provide the most accurate hand locations.

5.1.1. Main Findings

Results obtained from comparing outputs from DHMs driven by different motion capture systems indicated that hand locations of the model created with VIVE body tracking were most accurate compared to real-world hand locations. For all hand locations evaluated in this study, an overall RMS error of 13.7 cm was computed. The lowest horizontal distance error of 8 cm was obtained when utilizing the Vive Trackers as an input to the DHM. Upon examining the horizontal displacements, the Vive body tracking system provided the closest values to those of the actual location across horizontal and vertical target locations. This result were both supported and contradicting to that of the previous literature (Merker et al, 2023; Vox et al., 2021) which found that joint angle and positional data derived from inverse kinematic data from each HTC Vive trackers were not sufficient enough to perform a biomechanical analysis. To our knowledge, little research has been conducted regarding the comparison between DHMs created within *Process Simulate* that are driven by Vive trackers and IMU systems for ergonomic risk assessment.

These results suggest that proactive DHM assessments conducted in *Process Simulate* using kinematics inputs from Vive trackers can produce results similar, if not more accurate, than higher cost inertial and optical motion capture systems. Results from the IMU system indicated that there was an overall hand location RMS error of 24.3 cm. When separated by vertical and horizontal target locations, similar to the Vive results, IMU data showed an increase in error as horizontal target locations were further. Unlike results from previous literature (Sfalcin et al, 2019), overall increased error was found at the middle vertical target location as opposed to lower target locations where trunk flexion angle is increased. We hypothesized that the optical motion capture system would produce DHM hand locations most similar to the actual locations, as these were the same marker datasets that were used by the DHM software, but that was not the case. This finding reveals an important consideration; the hand location errors that are reported in this thesis are the result of not only motion capture system errors, but also in how the *Process Simulate* software uses the incoming kinematics data to estimate DHM postures and motions of the manikin.

At horizontal and lateral hand location values, DHM outputs from the optical motion capture input showed a significantly increased error, compared to the actual locations, indicating the marker input from an optical system does not necessarily translate the same hand locations within a DHM output. This was not the case when displacements were stratified into each target location. For the horizontal distance hand location, IMU values were more representative of findings from previous studies incorporating DHMs, where low vertical target locations and further horizontal target locations have seemingly increased errors. These IMU values tend to underestimate distances, resulting in an underestimation of physical demands. This can be observed in the Bland-Altman plot for Vertical displacement (V) for the IMU system (*figure 3.9*), as the data clusters increase relative to the mean error (y-axis) as vertical location increases (x-axis). Vertical hand distance values suggest consistent findings as Vive had fewer errors compared to the IMU system. This point is further confirmed by the smaller 95% limits of agreement as shown in *figure 3.10,* indicating that the Vive system is more likely to agree with actual location values compared to the other two systems. The IMU system had a consistent error of roughly 26.3 cm compared to the actual location across the high and middle vertical target location. All the systems remained consistent over vertical hand values as reach increased. As for the lateral displacement values, significant differences were found between the IMU, Vive, and actual location pairings at the left lateral target locations across all vertical target locations. All of the motion capture systems processed through the DHM consistently showed a positive error on hand location compared to the actual location, indicating that on the left targets, the system inputs were overestimating hand locations. This case was the opposite for the right lateral target locations where hand location values of the Vive and IMU systems were underestimating lateral displacements compared to the actual location and the optical system. Even so, all of the lateral displacement values indicated an increase as the hand locations moved further to the right target locations, which is in agreement with previous literature on the presence of depth perception issues related to VR (Jamiy & Marsh, 2019; Choe et al., 2021).

In addition to examining the accuracy of the horizontal, vertical and lateral displacements of the hands, this thesis also aimed to explore what the downstream effects of these positional errors may be for exposure variables relevant to ergonomics analysis (e.g. spine compression and joint angles). For spine compression, the greatest differences between the three motion capture systems were present at low vertical target locations at further horizontal reach locations. The IMU system showed consistent errors across all vertical target locations, as it significantly underestimated spine compression values compared to those values from the Vive system. This pattern is also present with the hand location outcomes, as the horizontal, vertical, and lateral distance of the hand all play a role in the loading of the spine (Waters, 1993). Lower vertical distance, as well as further horizontal reach distance, would lead to higher spine compression values, causing higher loading on the low back. The horizontal and vertical hand distances directly influence the compression of the spine through flexion and extension of the spine. In this study, at low vertical and further horizontal target locations, spine compression was shown to have greater differences between systems. At low table heights, the IMU spine compression was 82 N lower than Vive, presenting a 6% difference, and 213 N lower than the optical system (16% difference). Similarly, for further reaches, the IMU system estimated 184 N less spine compression than the Vive (16% difference), and 100 N lower than the optical system (11% difference). A connection between the hand location and spine compression can be seen as errors generally worsened at further reaches and lower heights consistently underestimating hand location magnitudes, resulting in up to 16% lower spine compression values. These differences are large enough to be considered functionally relevant, especially considering a NIOSH spine compression criterion of 3400 N (Waters, 1993). The findings of this study did not reach spine compression values near that threshold limit as the largest absolute spine compression value was at 2248 N. This was, however, without the implementation of object loads within the DHM which could possibly result in higher compression values. With errors within 5-10% of this ergonomics threshold, this can have an important impact on whether a task is considered acceptable or unacceptable, especially when the concept of cumulative loading is introduced into the assessment. As a reach task in a manufacturing assembly setting would have larger frequencies than that of this study, cumulative loading over time should be considered when conducting work task simulations (Sultan et al., 2018). This means that, even when the NIOSH spine compression threshold of 3400 N is not reached, some loading of the spine over large frequencies could increase overall physical demands. Ultimately, the spine compression results from this study should be taken into account when conducting an ergonomics assessment, erring on the side of caution when making decisions.

Differences in trunk flexion angle would also be responsible for the results of spine compression measurements. Spine flexion angles between the three systems were quite similar at all three vertical target locations, and with increasing horizontal reaches. At lower vertical target locations, the IMU system was minimally underpredicting trunk flexion at only a 8-degree difference to the optical system and a 3 degrees compared to the Vive, but would stay similar at other vertical target locations. However, this was not the case with shoulder and elbow flexion angles. The shoulder flexion angle suggests that the further the horizontal distance was, the greater the error between the IMU system was compared to other systems. At all vertical target locations, distinct differences were seen between all the systems and those differences are consistent across all targets. Notably, the joint angles from IMU DHM data was shown to be underestimated by up to 39.6 degrees to Vive and 22.4 degrees to the optical system at the furthest horizontal distance and high target locations. Similarly, joint angles calculated from the Vive input are consistently greater than the other systems across all target locations. This trend was not present in elbow flexion angles. Results for elbow flexion angles between the three systems suggest that at higher vertical target locations, all systems showed similar elbow flexion angles, but did not show the same results at the mid or low target locations. This suggests the possibility that the discrepancy between the systems could be driven by how joint angles are computed or how hand locations were determined using these joint angles in the DHM. Previous studies (Schepers et al., 2018; Roetenberg et al., 2013; Robert-Lachaine et al., 2016; Mavor et al., 2020) have suggested that IMUs, specifically Xsens, have accurate joint angle estimations with an RMSE of less than 3 degrees across all joints. As such, the increased error of elbow and shoulder joint angles may potentially be due to computational inconsistencies within the Process Simulate DHM.

5.1.2. Limitations and Assumptions

Limitations presented by each motion capture system should be considered during the analysis of the results presented. The Vive, IMUs, and optical motion capture systems all require attachment of surface level trackers, markers, and sensors on segments of interest, potentially restricting or discouraging certain movements within the range of motion of the participant. All attached trackers were ensured to place no limitations on participant's movement, determined through verbal confirmation from participants indicating that trackers were not interfering with the range of motion of the upper limb. Additionally, each motion capture system was recorded and instrumented concurrently, which introduces the possibility of signal interference or distortion between systems. A further analysis should be conducted to verify what potential effect concurrently measuring with these systems may have on the final outcome variables. Another limitation to this study relating to each motion capture system was the absence of accounting drift present at both the IMU and the Vive systems.

There were also some potential limitations with the VR technology to consider. The VR head-mounted display (HMD) was securely placed on the participant's head along with verbal confirmation from participants which indicated secure fitting and clear vision of the virtual environment. Controllers were handed to the participants, and all feedback were either visual or haptic through vibration of the controllers. Different movement strategies may arise as each participant would have to rely on virtual depictions of the controllers and haptic feedback to embody the DHM. The variability of participants who have and have not experienced instrumentation and utilizing a VR headset before could potentially influence the way they move within VR. There is potential that the variability observed in the participant's hand location was influenced by the position of the controller during the task simulation. Due to the lack of physical restrictions, variability could potentially be present at the endpoint of each target where the participant “lets go” of the object. This could possibly influence how the participant conducts the reaching task. However, as this thesis evaluated kinematics between DHM-outputs and comparisons to true kinematics marker data from concurrent collection, any behavioural differences would not have factored into these results. Another limitation to this study is that participants were only conducting one-armed reaches, which means this data does not necessarily represent two-handed reaching or left-arm reaching. This should be considered in future research.

Each motion capture systems’ capabilities and accuracies are already known based on their respective technical specifications and previous evidence. However, in this study, kinematic data from each system was used to drive movement of a DHM, adding further calculations of pose estimation to biomechanical models created on each native motion capture software. As such, this study does not fully compare data from each motion capture system, but DHMs and estimations derived from data from each system. In order to fully determine the accuracy of each motion capture system, raw data should be processed and analyzed in its native software. This would result in an actual comparison between IMUs and other systems outside the need of a DHM (Chung et al., 2011; Das et al., 2023).

One additional factor that requires some further consideration were some of the large outliers present in the data. For example, the Bland-Altman plots indicated several substantial outliers for the IMU horizontal, lateral, and vertical hand displacement values, and Vive horizontal hand values. For the purposes of this thesis, and to provide a fair analysis of the overall scope of errors produced by this DHM VR process, we chose to leave these outliers in the dataset, as similar outliers could potentially be present if a VR analysis were conducted by an ergonomist in the field today (and they would have no way of knowing the magnitude or direction of some of these potential errors). The source of these outliers are unknown at this time and needs to be investigated more thoroughly, but one possibility could be due to scaling inconsistencies within the DHM. At this point, version 2307 of *Process Simulate* was used as the DHM to generate body tracking inputs into ergonomics outputs. Since then, Siemens recently implemented several changes to its biomechanical model structure, which would potentially result in a smoother and clearer operation of the simulation. Utilizing other DHM software packages may have different results from current findings as only Process Simulate was used to calculate and analyze outcome measures.

5.1.3. Future Directions

Though the target-based approach in this study allowed for a systematic evaluation of errors at certain points throughout the reach envelope, this methodology unfortunately only leverages a small percentage of the overall available data. Future research should examine ergonomics outcome measures through a dynamic method instead of a static "target" approach. For example, all 3 systems can be compared across an entire cycle of multiple movements (e.g. an entire build process). Comparisons between VR and physical reach simulations would need to be conducted to determine the effects of simulating work in VR. Though not presented in this thesis, an additional condition was also collected, where the exact same target-based object placement task was replicated in physical reality, using an actual table with targets and a physical cylindrical object - all of the same dimensions as the VR task. This was not presented due to time constraints on the thesis timeline. Future analysis of this dataset will allow for a comparison of how movement behaviour differs in a

VR environment relative to conducting the exact same task in reality, and what the potential effect of these differences may be on the ergonomics parameters evaluated in this study.

Further comparing kinematics data with and without the use of a DHM could potentially lead to a more complete understanding of how these motion capture systems work individually. Additionally, further research to investigate estimates at further reach distances along a reach envelope (such as overhead tasks) would need to be conducted, while also incorporating other tracking methods that may influence grasping movement strategies. For example, using Manus Quantum VR gloves in future research, instead of relying on controllers, could possibly affect the accuracy of reach dimensions and result in simulating more natural movement strategies of participants.

5.2. Conclusion

Hand location values calculated from the Vive tracker resulted in the smallest positional errors relative to the actual hand location values. As the least costly motion capture system, the Vive trackers were able to showcase lower overall errors compared to the optical and IMU systems and provide accurate simulation of real-world hand locations through the use of a DHM software package (Siemens Process Simulate Human). The findings of this study generally agree with previous literature where IMU systems provide increased errors at further and lower reach distances, especially at increased trunk flexion angle. Throughout several target locations, the IMU system consistently underestimated the hand location, especially at lower vertical and furthest horizontal target locations. Similarly, upper limb joint angles were also underestimated at all of the target locations. However, it should be noted that all of the outcome measures were collected through one DHM software package, that may conduct additional computations to motion capture data from various systems to its biomechanical model. Results from this study contradict previous literature in which the Vive trackers were inaccurate enough to be used for biomechanical risk assessments (Merker et al., 2023). The use of a DHM software that receives independent inverse kinematic data of each tracker's position and reconstructing said model into a biomechanical model resulted in greater accuracy compared to models generated based on other motion capture systems. The errors present from the two other motion capture systems are outside of their respective controls as all human models were created in *Process Simulate.* This indicates the further need of communication and integration to reduce these errors in model calculation and pose estimation. Nonetheless, this impact may not provide the same results when comparing direct outcomes from each system's respective native software or other DHM software packages. It is, however, concluded that while using *Process Simulate* for ergonomics risk assessment, the most optimal and accurate system would be the Vive motion capture system.

Though further evaluation is necessary, this is a promising finding, as the use of the Vive VR and tracking system represents a relatively low cost, easy set-up and commercially accessible option for ergonomists to conduct virtual ergonomics analyses in VR. Based on this study, the DHM generated using kinematic data from the Vive VR tracker system provides the most similar results as those of the actual hand location. As such, until development and biomechanical model integration between motion capture system software to *Process Simulate* and other DHMs are further supported, the HTC Vive Trackers are a cost-effective system to invest in.

REFERENCES

Agostinelli, T., Generosi, A., Ceccacci, S., Khamaisi, R. K., Peruzzini, M., & Mengoni, M. (2021). Preliminary Validation of a Low-Cost Motion Analysis System Based on RGB Cameras to Support the Evaluation of Postural Risk Assessment. *Applied Sciences*, *11*(22), 10645.

Ahmed, S., Irshad, L., Demirel, H. O., & Tumer, I. Y. (2019). A Comparison Between Virtual Reality and Digital Human Modeling for Proactive Ergonomic Design. In V. G. Duffy (Ed.), *Digital Human Modeling and Applications in Health, Safety, Ergonomics and Risk Management. Human Body and Motion* (Vol. 11581, pp. 3–21). Springer International Publishing. https://doi.org/10.1007/978-3-030-22216-1_1

Andrews, T., Searcy, B., & Wallace, B. (2020). Using Virtual Reality and Motion Capture as Tools for Human Factors Engineering at NASA Marshall Space Flight Center. In T. Ahram (Ed.), *Advances in Artificial Intelligence, Software and Systems Engineering* (Vol. 965, pp. 399–408). Springer International Publishing. https://doi.org/10.1007/978-3-030-20454-9_41

Beese, N. O., Reinhard, R., & Lachmann, T. (2022). The right tools for the job: Towards preference and performance considerations in the design of Virtual Reality interactions. *33rd European Conference on Cognitive Ergonomics*, 1–5. https://doi.org/10.1145/3552327.3552349

Begon, M., Colloud, F., Fohanno, V., Bahuaud, P., & Monnet, T. (2009). Computation of the 3D kinematics in a global frame over a 40 m-long pathway using a rolling motion analysis system. *Journal of Biomechanics*, *42*(16), 2649–2653. https://doi.org/10.1016/j.jbiomech.2009.08.020

Birckhead, B., Khalil, C., Liu, X., Conovitz, S., Rizzo, A., Danovitch, I., Bullock, K., & Spiegel, B. (2019). Recommendations for Methodology of Virtual Reality Clinical Trials in Health Care by an International Working Group: Iterative Study. *JMIR Mental Health*, *6*(1), e11973. https://doi.org/10.2196/11973

Caserman, P., Garcia-Agundez, A., Konrad, R., Göbel, S., & Steinmetz, R. (2019). Real-time body tracking in virtual reality using a Vive tracker. *Virtual Reality*, *23*(2), 155–168. https://doi.org/10.1007/s10055-018-0374-z

Chaffin, D. B. (2001). *Digital Human Modeling for Vehicle and Workplace Design* (1st ed). SAE International.

Chaffin, D. B. (2005). Primary prevention of low back pain through the application of biomechanics in manual materials handling tasks. *G Ital Med Lav Erg*, *27*(1), 40–50.

Das, P., Joo, S., & Lee, Y. (2023). *Concurrent Validity Study of 3D Motion Measurement Systems: VICON vs. Xsens* (Doctoral dissertation, Grand Valley State University).

Da Silva, A. G., Mendes Gomes, M. V., & Winkler, I. (2022). Virtual Reality and Digital Human Modeling for Ergonomic Assessment in Industrial Product Development: A Patent and Literature Review. *Applied Sciences*, *12*(3), 1084. https://doi.org/10.3390/app12031084

Demirel, H. O., Ahmed, S., & Duffy, V. G. (2022). Digital Human Modeling: A Review and Reappraisal of Origins, Present, and Expected Future Methods for Representing Humans Computationally. *International Journal of Human–Computer Interaction*, *38*(10), 897–937. https://doi.org/10.1080/10447318.2021.1976507

Falck, A.-C., & Rosenqvist, M. (2014). A model for calculation of the costs of poor assembly ergonomics (part 1). *International Journal of Industrial Ergonomics*, *44*(1), 140–147. https://doi.org/10.1016/j.ergon.2013.11.013

Fewster, K. M., & Potvin, J. R. (2015). An Investigation of Leaning Behaviors During One-Handed Submaximal Exertions with Extended Reaches. *IIE Transactions on Occupational Ergonomics and Human Factors*, *3*(3–4), 188–196. https://doi.org/10.1080/21577323.2015.1042096

Fischer, C., Rupprecht, P., & Schlund, S. (2023). *Different approaches of conducting ergonomic assessment utilizing digital human models and motion capture in industrial site assembly*. Intelligent Human Systems Integration (IHSI 2023) Integrating People and Intelligent Systems. https://doi.org/10.54941/ahfe1002854

Fritzsche, L. (2010). Ergonomics risk assessment with digital human models in car assembly: Simulation versus real life. *Human Factors and Ergonomics in Manufacturing & Service Industries*, *20*(4), 287–299. https://doi.org/10.1002/hfm.20221

Gallagher, S., & Heberger, J. R. (2013). Examining the Interaction of Force and Repetition on Musculoskeletal Disorder Risk: A Systematic Literature Review. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *55*(1), 108–124. https://doi.org/10.1177/0018720812449648

Geiger, A., Bewersdorf, I., Brandenburg, E., & Stark, R. (2018). Visual Feedback for Grasping in Virtual Reality Environments for an Interface to Instruct Digital Human Models. In T. Ahram & C. Falcão (Eds.), *Advances in Usability and User Experience* (Vol. 607, pp. 228–239). Springer International Publishing. https://doi.org/10.1007/978-3-319-60492-3_22

Geiger, A., Brandenburg, E., & Stark, R. (2020). Natural Virtual Reality User Interface to Define Assembly Sequences for Digital Human Models. *Applied System Innovation*, *3*(1), 15. https://doi.org/10.3390/asi3010015

Geiselhart, F., Otto, M., & Rukzio, E. (2016). On the Use of Multi-Depth-Camera Based Motion Tracking Systems in Production Planning Environments. *Procedia CIRP*, *41*, 759–764. https://doi.org/10.1016/j.procir.2015.12.088

Godin, C., Chiang, J., Stephens, A., & Potvin, J. (2006). *Assessing the Accuracy of Ergonomic Analyses when Human Anthropometry is Scaled in a Virtual Environment*. 2006-01–2319. https://doi.org/10.4271/2006-01-2319

Gonçalves, G., Melo, M., Barbosa, L., Vasconcelos-Raposo, J., & Bessa, M. (2022). Evaluation of the impact of different levels of self-representation and body tracking on the sense of presence and embodiment in immersive VR. *Virtual Reality*, *26*(1), 1–14. https://doi.org/10.1007/s10055-021-00530-5

Gonzalez-Franco, M., Cohn, B., Ofek, E., Burin, D., & Maselli, A. (2020). The Self-Avatar Follower Effect in Virtual Reality. *2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, 18–25. https://doi.org/10.1109/VR46266.2020.00019

Grajewski, D., Górski, F., Zawadzki, P., & Hamrol, A. (2013). Application of Virtual Reality Techniques in Design of Ergonomic Manufacturing Workplaces. *Procedia Computer Science*, *25*, 289–301. https://doi.org/10.1016/j.procs.2013.11.035

Grandi, F., Khamaisi, R. K., Morganti, A., Peruzzini, M., & Pellicciari, M. (2024). Human-Centric Design of Automated Production Lines Using Virtual Reality Tools and Human Data Analysis. In F. J. G. Silva, L. P. Ferreira, J. C. Sá, M. T. Pereira, & C. M. A. Pinto (Eds.), *Flexible Automation and Intelligent Manufacturing: Establishing Bridges for More Sustainable Manufacturing Systems* (pp. 518–526). Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-38165-2_61

Hamurcu, A., Timur, Ş., & Rızvanoğlu, K. (2023). A Study on the Adoption of Virtual Reality in Industrial Design Education. *IEEE Transactions on Learning Technologies*, *16*(6), 900–913. https://doi.org/10.1109/TLT.2023.3321292

Hara, M., Kitamura, T., Murakawa, Y., Shimba, K., Yamaguchi, S., & Tamaki, M. (2018). Safety and Feasibility of Dual-task Rehabilitation Program for Body Trunk Balance Using Virtual Reality and Three-dimensional Tracking Technologies. *Progress in Rehabilitation Medicine*, *3*(0), n/a. https://doi.org/10.2490/prm.20180016mail

Harari, Y., Bechar, A., & Riemer, R. (2020). Workers' biomechanical loads and kinematics during multiple-task manual material handling. *Applied Ergonomics*, *83*, 102985. https://doi.org/10.1016/j.apergo.2019.102985

Holzwarth, V., Gisler, J., Hirt, C., & Kunz, A. (2021). Comparing the Accuracy and Precision of SteamVR Tracking 2.0 and Oculus Quest 2 in a Room Scale Setup. *2021 the 5th International Conference on Virtual and Augmented Reality Simulations*, 42–46. https://doi.org/10.1145/3463914.3463921

Jaffar, N., Abdul-Tharim, A. H., Mohd-Kamar, I. F., & Lop, N. S. (2011). A Literature Review of Ergonomics Risk Factors in Construction Industry. *Procedia Engineering*, *20*, 89–97. https://doi.org/10.1016/j.proeng.2011.11.142

Jäger, M., & Luttmann, A. (1992). The load on the lumbar spine during asymmetrical bi-manual materials handling. *Ergonomics*, *35*(7–8), 783–805. https://doi.org/10.1080/00140139208967363

Ji, X., Piovesan, D., & Conley, K. (2022). The Effect of Pulling Effort on Lumbar Spine via Applying Digital Human Modeling Technology. *IISE Annual Conference. Proceedings*, 1–6.

Ji, X., & Tiari, S. (2022). Posture evaluation for the full-body dynamic simulation in JACK Siemens PLM. *International Journal of Human Factors and Ergonomics*, *9*(3), 261. https://doi.org/10.1504/IJHFE.2022.126127

Jones, J. A., Swan, J. E., Singh, G., & Ellis, S. R. (2011). Peripheral visual information and its effect on distance judgments in virtual and augmented environments. *Proceedings of the ACM SIGGRAPH Symposium on Applied Perception in Graphics and Visualization*, 29–36. https://doi.org/10.1145/2077451.2077457

Juliano, J. M., & Liew, S.-L. (2020). Transfer of motor skill between virtual reality viewed using a head-mounted display and conventional screen environments. *Journal of NeuroEngineering and Rehabilitation*, *17*(1), 48. https://doi.org/10.1186/s12984-020-00678-2

Kajaks, T., Stephens, A., & Potvin, J. R. (2011). The effect of manikin anthropometrics and posturing guidelines on proactive ergonomic assessments using digital human models. *International Journal of Human Factors Modelling and Simulation*, *2*(3), 236. https://doi.org/10.1504/IJHFMS.2011.044512

Kazemi, R., & Lee, S. C. (2024). Human Factors/Ergonomics (HFE) Evaluation in the Virtual Reality Environment: A Systematic Review. *International Journal of Human–Computer Interaction*, *40*(17), 4533–4549. https://doi.org/10.1080/10447318.2023.2227835

Kourtesis, P., Linnell, J., Amir, R., Argelaguet, F., & MacPherson, S. E. (2023). Cybersickness in Virtual Reality Questionnaire (CSQ-VR): A Validation and Comparison against SSQ and VRSQ. *Virtual Worlds*, *2*(1), 16–35. https://doi.org/10.3390/virtualworlds2010002

La Delfa, N. J., Kunasegaram, A., Whittaker, R., & Dickerson, C. R. (2021). Determining best practices for manual pill crushing through evaluation of upper extremity muscle exposures. *Applied Ergonomics*, *90*, 103275. https://doi.org/10.1016/j.apergo.2020.103275

La Delfa, N. J., & Potvin, J. R. (2016). Multidirectional manual arm strength and its relationship with resultant shoulder moment and arm posture. *Ergonomics*, *59*(12), 1625–1636. https://doi.org/10.1080/00140139.2016.1157628

La Delfa, N. J., Whittaker, R. L., Lockley, R. M. E., Fournier, D. E., & Dickerson, C. R. (2022). The sensitivity of shoulder muscle fatigue to vertical hand location during complex manual force exertions. *International Journal of Industrial Ergonomics*, *88*, 103272. https://doi.org/10.1016/j.ergon.2022.103272

Lawson, G., Salanitri, D., & Waterfield, B. (2016). Future directions for the development of virtual reality within an automotive manufacturer. *Applied Ergonomics*, *53*, 323–330. https://doi.org/10.1016/j.apergo.2015.06.024

Lin, C.-L., Wang, M.-J. J., Drury, C. G., & Chen, Y.-S. (2010). Evaluation of perceived discomfort in repetitive arm reaching and holding tasks. *International Journal of Industrial Ergonomics*, *40*(1), 90–96. https://doi.org/10.1016/j.ergon.2009.08.009

Malik, A. A., Masood, T., & Bilberg, A. (2020). Virtual reality in manufacturing: Immersive and collaborative artificial-reality in design of human-robot workspace. *International Journal of Computer Integrated Manufacturing*, *33*(1), 22–37. https://doi.org/10.1080/0951192X.2019.1690685

Mavor, M. P., Ross, G. B., Clouthier, A. L., Karakolis, T., & Graham, R. B. (2020). Validation of an IMU Suit for Military-Based Tasks. *Sensors*, *20*(15), 4280. https://doi.org/10.3390/s20154280

Marras, W. S., & Davis, K. G. (1998). Spine loading during asymmetric lifting using one versus two hands. *Ergonomics*, *41*(6), 817–834. https://doi.org/10.1080/001401398186667

Menolotto, M., Komaris, D.-S., Tedesco, S., O'Flynn, B., & Walsh, M. (2020). Motion Capture Technology in Industrial Applications: A Systematic Review. *Sensors*, *20*(19), 5687. https://doi.org/10.3390/s20195687

Merker, S., Pastel, S., Bürger, D., Schwadtke, A., & Witte, K. (2023). Measurement Accuracy of the HTC VIVE Tracker 3.0 Compared to Vicon System for Generating Valid Positional Feedback in Virtual Reality. *Sensors*, *23*(17), 7371. https://doi.org/10.3390/s23177371

Merriaux, P., Dupuis, Y., Boutteau, R., Vasseur, P., & Savatier, X. (2017). A Study of Vicon System Positioning Performance. *Sensors*, *17*(7). https://doi.org/10.3390/s17071591

Mital, A., Nicholson, A. S., & Ayoub, M. M. (1997). *A guide to manual materials handling* (2. ed). Taylor & Francis.

Naddeo, A., D'Ambrosio, D., & Antonini, B. (2018). Task Analysis and Comfort Evaluation Through Simulations: Differences Between Subjective Perceptions and Simulated Data in the Case of Car-Hood Lifting. In R. H. M. Goossens (Ed.), *Advances in Social & Occupational Ergonomics* (Vol. 605, pp. 272–285). Springer International Publishing. https://doi.org/10.1007/978-3-319-60828-0_28

Niehorster, D. C., Li, L., & Lappe, M. (2017). The Accuracy and Precision of Position and Orientation Tracking in the HTC Vive Virtual Reality System for Scientific Research. *I-Perception*, *8*(3), 204166951770820. https://doi.org/10.1177/2041669517708205

O'Neil, B. A., Forsythe, M. E., & Stanish, W. D. (2001). Chronic occupational repetitive strain injury. *Canadian Family Physician Medecin De Famille Canadien*, *47*, 311–316.

Otto, M., Lampen, E., Agethen, P., Langohr, M., Zachmann, G., & Rukzio, E. (2019). A Virtual Reality Assembly Assessment Benchmark for Measuring VR Performance & Limitations. *Procedia CIRP*, *81*, 785–790. https://doi.org/10.1016/j.procir.2019.03.195

Potvin, J. R. (1997). Use of NIOSH equation inputs to calculate lumbosacral compression forces. *Ergonomics*, *40*(7), 691–707. https://doi.org/10.1080/001401397187847

Robert-Lachaine, X., Mecheri, H., Larue, C., & Plamondon, A. (2017). Validation of inertial measurement units with an optoelectronic system for whole-body motion analysis. *Medical & Biological Engineering & Computing*, *55*(4), 609–619. https://doi.org/10.1007/s11517-016-1537-2

Roetenberg, D., Luinge, H., & Slycke, P. (2009). Xsens MVN: Full 6DOF Human Motion Tracking Using Miniature Inertial Sensors. *Xsens Motion Technol. BV Tech.*, *3*. https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=cc2ba84a4d6e06fd85ad434f5b1a8545c1cc993c

Sagnier, C., Loup-Escande, E., & Vallèry, G. (2020). Effects of Gender and Prior Experience in Immersive User Experience with Virtual Reality. In T. Ahram & C. Falcão (Eds.), *Advances in Usability and User Experience* (pp. 305–314). Springer International Publishing.

Schepers, M., Giuberti, M., & Bellusci, G. (2018). *Xsens MVN: Consistent Tracking of Human Motion Using Inertial Sensing*. https://doi.org/10.13140/RG.2.2.22099.07205

Schlagenhauf, F., Sreeram, S., & Singhose, W. (2018). Comparison of Kinect and Vicon Motion Capture of Upper-Body Joint Angle Tracking. *2018 IEEE 14th International Conference on Control and Automation (ICCA)*, 674–679. https://doi.org/10.1109/ICCA.2018.8444349

Sfalcin, B., Ji, X., Gouw, A. D., Potvin, J., & Cort, J. (2019). Optical and inertial motion capture joint angle comparison using Jack™. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, *63*(1), 1137–1141. https://doi.org/10.1177/1071181319631153

Siemens PLM. (2024,11). *Process Simulate Support Center*. https://docs.sw.siemens.com/en-US/doc/288782031/PL20240711701594122.tecnomatix_eMS.xid1015765/xid1997987

Snook, S. H. (1978). The Ergonomics Society The Society's Lecture 1978. THE DESIGN OF MANUAL HANDLING TASKS. *Ergonomics*, *21*(12), 963–985. https://doi.org/10.1080/00140137808931804

Sommerich, C. M., Mcglothlin, J. D., & Marras, W. S. (1993). Occupational risk factors associated with soft tissue disorders of the shoulder: A review of recent investigations in the literature. *Ergonomics*, *36*(6), 697–717. https://doi.org/10.1080/00140139308967931

Sultan, S., Abdel-Malek, K., Arora, J., & Bhatt, R. (2018). Human Simulation System for Injury Assessment Due to Repetitive Loading. In D. N. Cassenti (Ed.), *Advances in Human Factors in Simulation and Modeling* (Vol. 591, pp. 131–140). Springer International Publishing. https://doi.org/10.1007/978-3-319-60591-3_12

Tcha-Tokey, K., Christmann, O., Loup-Escande, E., & Richir, S. (2016). Proposition and Validation of a Questionnaire to Measure the User Experience in Immersive Virtual Environments. *The International Journal of Virtual Reality*, *16*, 33–48. https://doi.org/10.20870/IJVR.2016.16.1.2880

Thomas, J. S., France, C. R., Leitkam, S. T., Applegate, M. E., Pidcoe, P. E., & Walkowski, S. (2016). Effects of Real-World Versus Virtual Environments on Joint Excursions in Full-Body Reaching Tasks. *IEEE Journal of Translational Engineering in Health and Medicine*, *4*, 1–8. https://doi.org/10.1109/JTEHM.2016.2623787

Topley, M., & Richards, J. G. (2020). A comparison of currently available optoelectronic motion capture systems. *Journal of Biomechanics*, *106*, 109820. https://doi.org/10.1016/j.jbiomech.2020.109820

Veale, J. F. (2014). Edinburgh Handedness Inventory – Short Form: A revised version based on confirmatory factor analysis. *Laterality: Asymmetries of Body, Brain and Cognition*, *19*(2), 164–177. https://doi.org/10.1080/1357650X.2013.783045

Vox, J. P., Weber, A., Wolf, K. I., Izdebski, K., Schüler, T., König, P., Wallhoff, F., & Friemert, D. (2021). An Evaluation of Motion Trackers with Virtual Reality Sensor Technology in Comparison to a Marker-Based Motion Capture System Based on Joint Angles for Ergonomic Risk Assessment. *Sensors*, *21*(9), 3145. https://doi.org/10.3390/s21093145

Walmsley, C. P., Williams, S. A., Grisbrook, T., Elliott, C., Imms, C., & Campbell, A. (2018). Measurement of Upper Limb Range of Motion Using Wearable Sensors: A Systematic Review. *Sports Medicine - Open*, *4*(1), 53. https://doi.org/10.1186/s40798-018-0167-7

Wang, J., Shi, R., Xiao, Z., Qin, X., & Liang, H.-N. (2022). Effect of Render Resolution on Gameplay Experience, Performance, and Simulator Sickness in Virtual Reality Games. *Proceedings of the ACM on Computer Graphics and Interactive Techniques*, *5*(1), 1–15. https://doi.org/10.1145/3522610

Waters, T. R., Putz-Anderson, V., Garg, A., & Fine, L. J. (1993). Revised NIOSH equation for the design and evaluation of manual lifting tasks. *Ergonomics*, *36*(7), 749–776. https://doi.org/10.1080/00140139308967940

Wenk, N., Penalver-Andres, J., Buetler, K. A., Nef, T., Müri, R. M., & Marchal-Crespo, L. (2023). Effect of immersive visualization technologies on cognitive load, motivation, usability, and embodiment. *Virtual Reality*, *27*(1), 307–331. https://doi.org/10.1007/s10055-021-00565-8

White, C. M. (2015). Proactive Ergonomics: Stopping Injuries Before They Occur. *Professional Safety*, *60*(06), 69–73.

Whitman, L. E., Jorgensen, M., Hathiyari, K., & Malzahn, D. (2004). Virtual Reality: Its Usefulness for Ergonomic Analysis. *Proceedings of the 2004 Winter Simulation Conference, 2004.*, *2*, 665–670. https://doi.org/10.1109/WSC.2004.1371525

Whittaker, R. L., La Delfa, N. J., & Dickerson, C. R. (2019). Algorithmically detectable directional changes in upper extremity motion indicate substantial myoelectric shoulder muscle fatigue during a repetitive manual task. *Ergonomics*, *62*(3), 431–443. https://doi.org/10.1080/00140139.2018.1536808

Windolf, M., Götzen, N., & Morlock, M. (2008). Systematic accuracy and precision analysis of video motion capturing systems—Exemplified on the Vicon-460 system. *Journal of Biomechanics*, *41*(12), 2776–2780. https://doi.org/10.1016/j.jbiomech.2008.06.024

Wu, G., Van Der Helm, F. C. T., (DirkJan) Veeger, H. E. J., Makhsous, M., Van Roy, P., Anglin, C., Nagels, J., Karduna, A. R., McQuade, K., Wang, X., Werner, F. W., & Buchholz, B. (2005). ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion—Part II: Shoulder, elbow, wrist and hand. *Journal of Biomechanics*, *38*(5), 981–992. https://doi.org/10.1016/j.jbiomech.2004.05.042

APPENDICES

Appendix A

Consent Form to Participate in a Research Study

Title of Research Study: *Understanding Real-Time Motion Tracking in Proactive Ergonomics Analyses*

Name of Principal Investigator (PI): Dr. Nicholas La Delfa

PI's contact number(s)/email(s): 905-721-8668 ext 2139 /

nicholas.ladelfa@ontariotechu.ca

Name(s) of Co-investigator(s), Faculty Supervisor, Student Lead(s), etc., and contact number(s)/email(s):

1. Ryuta Dharmaputra, Graduate Student (ryuta.dharmaputra1@ontariotechu.net)

Departmental and institutional affiliation(s): Faculty of Health Sciences, Ontario Tech University

External Funder/Sponsor: None

Introduction:

You are invited to participate in a research study entitled "*Understanding Real-Time Motion Tracking in Proactive Ergonomics Analyses.*" You are being asked to take part in this research study. Please ensure that you read over the information about this study seen below in this form. This form includes details regarding the study's protocols, procedures, risks, and benefits that you should be aware of if you wish to participate. You should ask the Principal Investigator (PI) or study team to explain any details that you do not understand and make sure all questions are answered before signing the consent form. Before you make your decision, you may talk to anyone about this study. Participation in this study is voluntary.

Purpose and Procedure:

Purpose:

A primary goal in the field of ergonomics is to reduce the prevalence of occupational injuries through a better design of work tasks. Design of a work task falls under the proactive approach to an intervention, eliminating and/or reducing injury risk factors within a workplace before it is built. To do this, digital human models and virtual design software are used in designing a work task to maximize efficiency and cost-effectiveness. Traditionally, digital human models have been postured in a task simulation through manipulation of each joint in the human body. Due to the advancements in motion tracking technology, digital human models can now be postured using real-time motion capture of workers. However, the accuracy of these systems has yet to be validated and compared to a gold standard when conducting a full-body ergonomics analysis on reaching positions. As such, the main objectives of this proposed research are to 1) validate the accuracy of an inertial-based motion capture system when used for virtual ergonomics analyses compared to an optical-electronic system and 2) determine whether there are any differences between three motion capture systems when used for virtual reality (VR)-based ergonomics analyses. We believe that the validation of these motion capture systems will guide future users in making an informed decision on which system to use when conducting an ergonomics analysis in a virtual environment.

You have been invited to participate in this research study because you are between the ages of 18 and 35 years old, is not prone to motion sickness, and have not experienced upper or lower extremity pain, injury, or have had surgery within 12 months prior to data collection.

Procedures:

Upon arrival at the laboratory (ERC1096), each participant will be introduced to the equipment and environment used for the protocol. Participants will be asked to complete the informed consent after being introduced to the study's methodology. Each participant will be instructed to arrive at a predetermined time. After the participant has provided written consent to participating in this proposed research study, height, weight, foot or shoe length, shoulder height (ground to C7 spinal process), shoulder width (right to left distal tip of acromion), elbow span (right to left olecranon in T-pose), wrist span (right to left ulnar styloid in T-pose), arm span (tip of right fingers to tip of left fingers in T-pose), hip height (ground to most lateral bony prominence of greater trochanter), knee height (ground to lateral epicondyle on the femoral bone), and ankle height (ground to distal tip of lateral malleolus) will be measured. These measurements are required to properly calibrate the motion capture equipment. The participant will then be instrumented with 53-passive retro-reflective markers, 17 Xsens sensors, and the 6 HTC Vive 3.0 trackers (all non-invasive) as shown in *Figure 2*. Once instrumented, the participant will conduct the calibration processes for each system, following the user manual. Once calibration of the motion capture systems are achieved, the participant will perform the drill placement task at the randomized table heights physically.

<u>Physical Reality (PR) Tasks:</u>

The main experimental task consists of the participant grabbing a drill and placing it on several marked locations on a tabletop. After moving the drill through the 9 total target locations, participants will be given a 1-minute rest period before continuing with the next trial. Three trials will be performed at each table height.

<u>Virtual Reality (VR) Tasks:</u>

Following the physical reality tasks, participants will be instrumented with a virtual reality head-mounted display. Calibration and a familiarization period of up to 5 minutes of the virtual environment will take place. After the participant is properly oriented to the VR environment, they will perform the same drill placement task in VR as they previously did in PR. The drill, table and targets will all exist virtually, but not physically.

The VR tasks will be conducted using two methods of body tracking (Vive VR sensors and XSens inertial sensors). Each body tracking modality will be tested in a counter-balanced order. After conclusion of the first body tracking method, the participant will be given a 5-minute rest period while the researcher changes the body tracking method streamed into the headset. After the completion of the VR conditions, the participant will complete a 36-item User Experience-Immersive Virtual Environment questionnaire. This marks the end of the proposed experimental protocol.

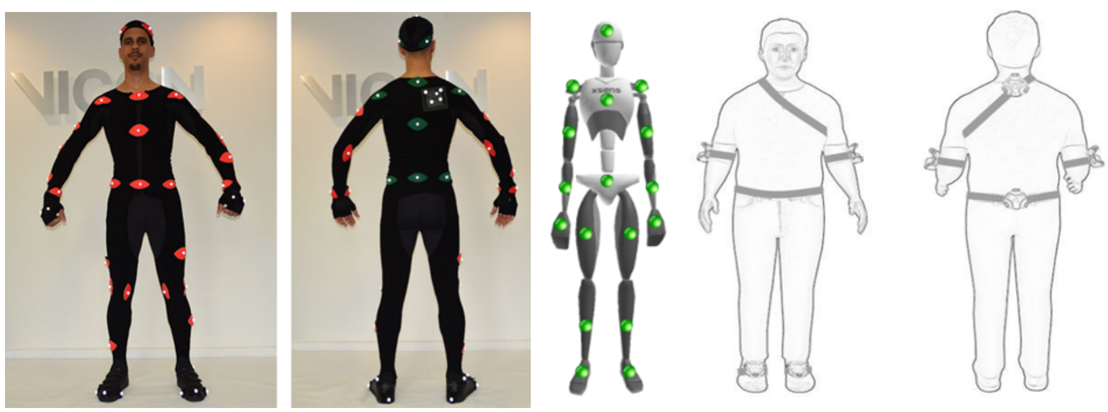

Figure 1 (from left to right): a. Vicon FrontWaist 53-Marker Placement Template (front and back), b. Xsens 17-Sensor Placement Template, c. 6-Tracker Vive 3.0 Tracker Placement Template

Potential Benefits:

This time in the lab allows students at Ontario Tech University to spend more time in the Kinesiology labs getting a better understanding of the equipment used. Additionally, this is a great opportunity to be exposed to what it would be like to conduct research. So, if this field intrigues you, this experience may be of great value.

Along with these direct benefits to you as a participant, you will be contributing to our scientific knowledge on the accuracy of motion capture systems for ergonomics use. These findings will hopefully be used to create an informed decision when using motion capture to posture a digital human model for ergonomics use.

Potential Risk or Discomforts:

The process of taping/sticking the kinematic markers may pose a slight risk of skin irritation from the tape's adhesive. These reactions are not significant, and they generally subside within 1-3 days. Participants will be instructed to wash and clean the area with soap where the tape was applied to mediate the problem. However, if the irritations continue to be a problem, we recommend that the participant proceed to the campus health clinic for advice regarding the irritations and contact the researchers to report the incident.

Another aspect of the study is the use of a virtual reality headset that may cause cybersickness, defined by a form of motion sickness that occurs as a result of exposure to immersive extended reality environments. Participants may experience disorientation, lightheadedness, and vertigo. These symptoms can last for hours. If participants experience any of the symptoms mentioned previously, they are to immediately contact the investigators and the research protocol will be stopped. If the cybersickness persists after 4 hours, it is best to seek professional medical attention. In the circumstance that any of the mentioned potential risks occurs, members of the research team have first aid training.

We will be collecting personal contact information that we must retain in order to follow up with you and/or conduct contact tracing if you may have been exposed to COVID-19 in coming to the research site.

As a result, we cannot guarantee the privacy and confidentiality of your participation in the study.

We cannot guarantee anonymity, as the personal contact information does identify you as a participant.

Contact information will be kept separate from data collection throughout the research study to allow for de-identification of the research data (If applicable, as detailed in the protocol).

During this time, the university may request information relating to all people entering and exiting our campus. As such please be advised that it may not be possible to keep your participation in a study confidential; however, no information about the data you share with us in the study will be shared outside of the research team.

You maintain your right to withdraw from the study, including research data (if applicable). If you do withdraw, we will continue to maintain your contact information and will only give it to Durham Public Health and the University if required for contact tracing.

If you think you have COVID-19 symptoms or have been in close contact with someone who has it, use the Government of Ontario's COVID-19 self-assessment tool and follow the instructions it provides to seek further care. In addition, you must inform the Principal Investigator immediately for follow-up.

There may be additional risks to participating in this research during the COVID-19 pandemic that are currently unforeseen and, therefore, not listed in this consent form. We have taken additional precautions to mitigate the known risks, which can be found in Appendix A.

Use and Storage of Data:

All collected data will be initially stored on a password-protected computer in the Occupational Neuromechanics & Ergonomics (ONE) Laboratory, then moved to an encrypted and password protected hard drive, which will be stored in a locked filing cabinet in the ONE lab. All data will also be backed up on an encrypted and password-protected Google Drive administered by Ontario Tech University and reviewed by our REB. All digital experimental data will be identified with a randomly assigned participant code (e.g. P123).

All participant consent forms, questionnaires and any other potentially identifying information (e.g. sex, age and anthropometric data) will be locked in a separate location; a locked filing cabinet in Dr. La Delfa's secure office. All consent forms, questionnaires and identifying information will be retained until the REB Project Completion form is submitted. After which, this identifying information will be destroyed. However, all anonymized experimental data will be retained indefinitely. Your data will be anonymized when all identifying information is destroyed. After this point, we will have no way of linking your data with you.

Please note that if your data is considered for use in a secondary analysis, we will seek appropriate REB approval before undertaking this analysis. Additionally, we will ask for your pre-consent to use these data in a potential secondary analysis, in case this analysis occurs after anonymization, and we cannot identify your data.

All information collected during this study, including your demographic and anthropometric data, will be kept confidential and will not be shared with anyone outside the study unless required by law. You will not be named in any reports, publications, or presentations that may come from this study.

Confidentiality:

Your privacy shall be respected. No information about your identity will be shared or published without your permission unless required by law. Confidentiality will be provided to the fullest extent possible by law, professional practice, and ethical codes of conduct. Please note that confidentiality cannot be guaranteed while data is in transit over the Internet. Also, the security of e-mail messages is not guaranteed. Messages may be forged, forwarded, kept indefinitely, or seen by others using the internet. Do not use email to discuss any information you think is sensitive. Do not use email in an emergency since e-mail may be delayed.

This research study includes the collection of demographic data which will be aggregated (not individually presented) in an effort to protect your anonymity. Despite best efforts, it is possible that your identity can be determined even when data is aggregated. However, we will minimize the potential of this occurrence by refraining from presenting any individual data. In practice, we typically only present mean and standard deviation data, which will make it impossible to identify one particular participant in our research.

Voluntary Participation:

Your participation in this study is voluntary and you may partake in only those aspects of the study in which you feel comfortable. You may also decide not to be in this study, or to be in the study now, and then change your mind later. You may leave the study at any time without affecting your academic standing, and/or research credit. You will be given information that is relevant to your decision to continue or withdraw from participation.

Right to Withdraw:

If you withdraw from the research project at any time, any data or human biological materials that you have contributed will be removed from the study and you do not need to offer any reason for making this request. However, after the REB Project Completion form is submitted and all the information linking you to the study is deleted. Researchers will be unable to remove your data, as we will have no method of identifying which data belongs to you. If study results are disseminated/published prior to the anonymization of your data, it will also be impossible to withdraw your data from the data set results after publication.

Conflict of Interest:

Researchers have an interest in completing this study. Their interests should not influence your decision to participate in this study.

Compensation. Reimbursement, Incentives:

As compensation for your time spent participating in this study, you will be offered extra course credit added to the Kinesiology course of your choosing (must be from the list of pre-confirmed courses options, which we will provide). By participating in this study, you will be offered 1% extra credit for every hour of participation to be put towards the final grade of your selected course. If you choose to forego the in-course credit or are not eligible (i.e., not enrolled in classes where it is offered), you will be remunerated with a $25 Amazon gift card. If you withdraw from this study for any reason, you will receive 1% extra credit for every hour of data collection attended or a pro-rated amount for a gift card based on time spent participating in the study ($10/hour, rounded up to the nearest hour). Should the parking gates at Ontario Tech University require payment during the day(s) of your participation, you will be provided with a parking voucher.

Debriefing and Dissemination of Results:

The data for this research may be submitted to scientific conferences and peer-reviewed journals for publication. Any published data will be free of any potentially identifying information. If you wish to receive an aggregate of the research findings, please check the box at the bottom of this form and provide an email address to receive the results.

Participant Rights and Concerns:

Please read this consent form carefully and feel free to ask the researcher any questions that you might have about the study. If you have any questions about your rights as a participant in this study, complaints, or adverse events, please contact the Research Ethics Office at (905) 721-8668 ext. 3693 or at researchethics@ontariotechuuoit.ca.

If you have any questions concerning the research study or experience any discomfort related to the study, please contact Ryuta Dharmaputra at ryuta.dharmaputra1@ontariotechu.net or Nicholas La Delfa at nicholas.ladelfa@ontariotechu.ca. By signing this form you do not give up any of your legal rights against the investigators, sponsor or involved institutions for compensation, nor does this form relieve the investigators, sponsor or involved institutions of their legal and professional responsibilities.

Consent to Participate (General):

I agree to participate in this study taking place at Ontario Tech University. I understand that my participation is optional. I confirm that I have read and understood the consent form and have been advised on the potential risks related to research involving human participants at this time.

By checking each of the boxes below, I acknowledge and agree with the statements as follows:

- I have read the consent form and understand the study being described;
- I have had an opportunity to ask questions and those questions have been answered. I am free to ask questions about the study in the future;
- I freely consent to participate in the research study, understanding that I may discontinue participation at any time without penalty. A copy of this consent form has been made available to me.

________________________ ________________________ ____________

Print Study Participant's Name | Signature | Date

My signature means that I have explained the study to the participant named above. I have answered all their questions.

________________________ ________________________ ____________

Print Name of Person Obtaining Signature Date

Request **dissemination** of results: ___ Yes ___ No

Email to contact: ____

Secondary Use of Research for Future Research Purposes

1. I understand the possible need for secondary research uses of my research data for future research use and provide consent for the use of my data to be used in future studies.

2. The research team has informed me that a separate REB application will be submitted for the secondary use of data for any future research purposes.

Participant must initial ________ Yes ________No

Appendix B

Table 1. Pairwise Comparisons between Systems for Horizontal Distance

contrast	*H Target*	*V Target*	*estimate*	*SE*	*df*	*t.ratio*	*p.value*
Actual Location - Optical	H_close	V_high	-103.97	16.65	43.89	-6.24	0.00
Actual Location - Vive	H_close	V_high	37.00	17.56	38.24	2.11	0.24
Actual Location - IMU	H_close	V_high	-8.63	26.97	21.19	-0.32	1.00
Optical - Vive	H_close	V_high	140.97	20.57	28.39	6.85	0.00
Optical - IMU	H_close	V_high	95.34	23.90	23.58	3.99	0.00
Vive - IMU	H_close	V_high	-45.63	30.76	19.47	-1.48	0.58
Actual Location - Optical	H_far	V_high	-5.44	16.65	43.89	-0.33	1.00
Actual Location - Vive	H_far	V_high	46.82	17.56	38.24	2.67	0.08
Actual Location - IMU	H_far	V_high	68.55	26.97	21.19	2.54	0.12
Optical - Vive	H_far	V_high	52.26	20.57	28.39	2.54	0.11
Optical - IMU	H_far	V_high	73.99	23.90	23.58	3.10	0.04
Vive - IMU	H_far	V_high	21.73	30.76	19.47	0.71	0.95
Actual Location - Optical	H_mid	V_high	-76.79	16.65	43.89	-4.61	0.00
Actual Location - Vive	H_mid	V_high	18.61	17.56	38.24	1.06	0.83
Actual Location - IMU	H_mid	V_high	18.27	26.97	21.19	0.68	0.96
Optical - Vive	H_mid	V_high	95.40	20.57	28.39	4.64	0.00
Optical - IMU	H_mid	V_high	95.06	23.90	23.58	3.98	0.00
Vive - IMU	H_mid	V_high	-0.34	30.76	19.47	-0.01	1.00
Actual Location - Optical	H_close	V_low	-95.70	16.83	45.81	-5.69	0.00
Actual Location - Vive	H_close	V_low	4.30	17.73	39.74	0.24	1.00
Actual Location - IMU	H_close	V_low	160.36	27.05	21.45	5.93	0.00
Optical - Vive	H_close	V_low	100.00	20.63	28.77	4.85	0.00

Optical - IMU	H_close	V_low	256.07	23.93	23.70	10.70	0.00
Vive - IMU	H_close	V_low	156.06	30.78	19.53	5.07	0.00
Actual Location - Optical	H_far	V_low	-10.91	16.83	45.81	-0.65	0.97
Actual Location - Vive	H_far	V_low	45.57	17.73	39.74	2.57	0.10
Actual Location - IMU	H_far	V_low	319.45	27.05	21.45	11.81	0.00
Optical - Vive	H_far	V_low	56.48	20.63	28.77	2.74	0.07
Optical - IMU	H_far	V_low	330.37	23.93	23.70	13.81	0.00
Vive - IMU	H_far	V_low	273.88	30.78	19.53	8.90	0.00
Actual Location - Optical	H_mid	V_low	-71.01	16.83	45.81	-4.22	0.00
Actual Location - Vive	H_mid	V_low	-4.04	17.73	39.74	-0.23	1.00
Actual Location - IMU	H_mid	V_low	229.32	27.05	21.45	8.48	0.00
Optical - Vive	H_mid	V_low	66.97	20.63	28.77	3.25	0.02
Optical - IMU	H_mid	V_low	300.33	23.93	23.70	12.55	0.00
Vive - IMU	H_mid	V_low	233.35	30.78	19.53	7.58	0.00
Actual Location - Optical	H_close	V_mid	-94.85	16.74	44.82	-5.67	0.00
Actual Location - Vive	H_close	V_mid	5.81	17.64	38.96	0.33	1.00
Actual Location - IMU	H_close	V_mid	89.34	27.02	21.36	3.31	0.02
Optical - Vive	H_close	V_mid	100.66	20.57	28.39	4.89	0.00
Optical - IMU	H_close	V_mid	184.20	23.90	23.58	7.71	0.00
Vive - IMU	H_close	V_mid	83.54	30.76	19.47	2.72	0.09
Actual Location - Optical	H_far	V_mid	-26.41	16.74	44.82	-1.58	0.52
Actual Location - Vive	H_far	V_mid	-0.07	17.64	38.96	-0.00	1.00
Actual Location - IMU	H_far	V_mid	211.65	27.02	21.36	7.83	0.00
Optical - Vive	H_far	V_mid	26.35	20.57	28.39	1.28	0.70
Optical - IMU	H_far	V_mid	238.07	23.90	23.58	9.96	0.00
Vive - IMU	H_far	V_mid	211.72	30.76	19.47	6.88	0.00

Actual Location - Optical	H_mid	V_mid	-70.58	16.74	44.82	-4.22	0.00
Actual Location - Vive	H_mid	V_mid	-14.42	17.64	38.96	-0.82	0.92
Actual Location - IMU	H_mid	V_mid	133.31	27.02	21.36	4.93	0.00
Optical - Vive	H_mid	V_mid	56.16	20.57	28.39	2.73	0.07
Optical - IMU	H_mid	V_mid	203.89	23.90	23.58	8.53	0.00
Vive - IMU	H_mid	V_mid	147.74	30.76	19.47	4.80	0.00

Table 2. Pairwise Comparisons between Systems for Vertical Distance

contrast	*V Target*	*estimate*	*SE*	*df*	*t.ratio*	*p.value*
Actual Location - Optical	V_high	53.00	33.31	15.73	1.59	0.52
Actual Location - Vive	V_high	50.59	16.91	18.18	2.99	0.05
Actual Location - IMU	V_high	263.86	26.82	16.16	9.84	0.00
Optical - Vive	V_high	-2.41	34.81	15.68	-0.07	1.00
Optical - IMU	V_high	210.86	36.77	15.61	5.73	0.00
Vive - IMU	V_high	213.27	22.18	16.76	9.62	0.00
Actual Location - Vicon	V_low	-26.05	33.34	15.79	-0.78	0.93
Actual Location - Vive	V_low	116.35	16.97	18.44	6.86	0.00
Actual Location - IMU	V_low	173.07	26.85	16.23	6.45	0.00
Optical - Vive	V_low	142.40	34.82	15.70	4.09	0.01
Optical - IMU	V_low	199.12	36.78	15.62	5.41	0.00
Vive - IMU	V_low	56.72	22.19	16.79	2.56	0.12
Actual Location - Vicon	V_mid	27.06	33.32	15.76	0.81	0.92
Actual Location - Vive	V_mid	76.08	16.94	18.30	4.49	0.00
Actual Location - IMU	V_mid	287.30	26.84	16.20	10.71	0.00
Optical - Vive	V_mid	49.01	34.81	15.68	1.41	0.63

Optical - IMU	V_mid	260.24	36.77	15.61	7.08	0.00
Vive - IMU	V_mid	211.23	22.18	16.76	9.52	0.00

Table 3. Pairwise Comparisons between Systems for Lateral Displacement

contrast	*V Target*	*L Target*	*estimate*	*SE*	*df*	*t.ratio*	*p.value*
Actual Location - Optical	V_high	L_left	-163.04	47.33	19.37	-3.45	0.02
Actual Location - Vive	V_high	L_left	92.25	24.71	47.77	3.73	0.00
Actual Location - IMU	V_high	L_left	-123.12	31.88	27.72	-3.86	0.01
Optical - Vive	V_high	L_left	255.30	46.47	19.58	5.49	0.00
Optical - IMU	V_high	L_left	39.92	56.01	17.95	0.71	0.95
Vive - IMU	V_high	L_left	-215.37	33.57	25.90	-6.42	0.00
Actual Location - Optical	V_low	L_left	-160.10	47.48	19.61	-3.37	0.02
Actual Location - Vive	V_low	L_left	100.62	24.99	49.95	4.03	0.00
Actual Location - IMU	V_low	L_left	-110.05	32.05	28.29	-3.43	0.01
Optical - Vive	V_low	L_left	260.72	46.54	19.70	5.60	0.00
Optical - IMU	V_low	L_left	50.05	56.04	17.99	0.89	0.90
Vive - IMU	V_low	L_left	-210.67	33.62	26.06	-6.27	0.00
Actual Location - Optical	V_mid	L_left	-146.80	47.40	19.48	-3.10	0.04
Actual Location - Vive	V_mid	L_left	100.68	24.85	48.83	4.05	0.00
Actual Location - IMU	V_mid	L_left	-97.48	31.99	28.08	-3.05	0.04
Optical - Vive	V_mid	L_left	247.48	46.47	19.58	5.33	0.00
Optical - IMU	V_mid	L_left	49.32	56.01	17.95	0.88	0.90
Vive - IMU	V_mid	L_left	-198.16	33.57	25.90	-5.90	0.00
Xsens - IMU	V_mid	L_left	42.57	35.30	24.41	1.21	0.75
Actual Location - Optical	V_high	L_mid	-83.05	47.34	19.39	-1.75	0.43

Actual Location - Vive	V_high	L_mid	137.25	24.71	47.77	5.55	0.00
Actual Location - IMU	V_high	L_mid	-37.21	31.88	27.72	-1.17	0.77
Optical - Vive	V_high	L_mid	220.30	46.48	19.60	4.74	0.00
Optical - IMU	V_high	L_mid	45.84	56.02	17.96	0.82	0.92
Vive - IMU	V_high	L_mid	-174.46	33.57	25.90	-5.20	0.00
Xsens - IMU	V_high	L_mid	-39.18	35.30	24.41	-1.11	0.80
Actual Location - Optical	V_low	L_mid	-101.11	47.49	19.63	-2.13	0.25
Actual Location - Vive	V_low	L_mid	142.56	24.99	49.95	5.70	0.00
Actual Location - IMU	V_low	L_mid	61.60	32.05	28.29	1.92	0.33
Optical - Vive	V_low	L_mid	243.67	46.55	19.72	5.23	0.00
Optical - IMU	V_low	L_mid	162.71	56.05	18.00	2.90	0.06
Vive - IMU	V_low	L_mid	-80.96	33.62	26.06	-2.41	0.14
Actual Location - Optical	V_mid	L_mid	-90.58	47.40	19.48	-1.91	0.34
Actual Location - Vive	V_mid	L_mid	135.32	24.85	48.83	5.45	0.00
Actual Location - IMU	V_mid	L_mid	50.19	31.99	28.08	1.57	0.53
Optical - Vive	V_mid	L_mid	225.90	46.47	19.58	4.86	0.00
Optical - IMU	V_mid	L_mid	140.77	56.01	17.95	2.51	0.13
Vive - IMU	V_mid	L_mid	-85.13	33.57	25.90	-2.54	0.11
Actual Location - Optical	V_high	L_right	-21.39	47.33	19.37	-0.45	0.99
Actual Location - Vive	V_high	L_right	142.12	24.71	47.77	5.75	0.00
Actual Location - IMU	V_high	L_right	62.88	31.88	27.72	1.97	0.31
Optical - Vive	V_high	L_right	163.51	46.47	19.58	3.52	0.02
Optical - IMU	V_high	L_right	84.27	56.01	17.95	1.50	0.57
Vive - IMU	V_high	L_right	-79.24	33.57	25.90	-2.36	0.16
Actual Location - Optical	V_low	L_right	-60.43	47.48	19.61	-1.27	0.71

Actual Location - Vive	V_low	L_right	156.05	24.99	49.95	6.24	0.00
Actual Location - IMU	V_low	L_right	274.33	32.05	28.29	8.56	0.00
Optical - Vive	V_low	L_right	216.48	46.54	19.70	4.65	0.00
Optical - IMU	V_low	L_right	334.76	56.04	17.99	5.97	0.00
Vive - IMU	V_low	L_right	118.28	33.62	26.06	3.52	0.01
Actual Location - Optical	V_mid	L_right	-56.97	47.40	19.48	-1.20	0.75
Actual Location - Vive	V_mid	L_right	128.11	24.85	48.83	5.16	0.00
Actual Location - IMU	V_mid	L_right	202.69	31.99	28.08	6.34	0.00
Optical - Vive	V_mid	L_right	185.08	46.47	19.58	3.98	0.01
Optical - IMU	V_mid	L_right	259.65	56.01	17.95	4.64	0.00
Vive - IMU	V_mid	L_right	74.57	33.57	25.90	2.22	0.20

Table 4. Pairwise Comparisons between Systems for Spine Compression

contrast	*V Target*	*estimate*	*SE*	*df*	*t.ratio*	*p.value*
Optical - Vive	V_high	-120.00	73.79	16.83	-1.63	0.39
Optical - IMU	V_high	15.63	108.12	15.82	0.14	1.00
Vive - IMU	V_high	135.63	93.33	16.11	1.45	0.49
Optical - Vive	V_low	-180.65	73.87	16.90	-2.45	0.11
Optical - IMU	V_low	394.58	108.15	15.83	3.65	0.01
Vive - IMU	V_low	575.23	93.36	16.13	6.16	0.00
Optical - Vive	V_mid	-250.31	73.79	16.83	-3.39	0.02
Optical - IMU	V_mid	68.13	108.12	15.82	0.63	0.92
Vive - IMU	V_mid	318.43	93.33	16.11	3.41	0.02

Table 5. Pairwise Comparisons between Systems for Trunk Flexion Angle

contrast	*V Target*	*H Target*	*estimate*	*SE*	*df*	*t.ratio*	*p.value*
Optical - Vive	V_high	H_close	-3.77	1.07	5004.00	-3.53	0.00
Optical - IMU	V_high	H_close	-1.31	1.07	5004.00	-1.22	0.61
Vive - IMU	V_high	H_close	2.46	1.07	5004.00	2.31	0.10
Optical - Vive	V_low	H_close	-9.32	1.08	5004.00	-8.64	0.00
Optical - IMU	V_low	H_close	4.99	1.07	5004.05	4.64	0.00
Vive - IMU	V_low	H_close	14.31	1.07	5004.05	13.33	0.00
Optical - Vive	V_mid	H_close	-9.89	1.07	5004.00	-9.26	0.00
Optical - IMU	V_mid	H_close	-4.32	1.07	5004.00	-4.05	0.00
Vive - IMU	V_mid	H_close	5.57	1.07	5004.00	5.21	0.00
Optical - Vive	V_high	H_far	7.02	1.07	5004.00	6.57	0.00
Optical - IMU	V_high	H_far	0.04	1.07	5004.00	0.04	1.00
Vive - IMU	V_high	H_far	-6.98	1.07	5004.00	-6.53	0.00
Optical - Vive	V_low	H_far	-9.64	1.08	5004.00	-8.93	0.00
Optical - IMU	V_low	H_far	5.14	1.07	5004.05	4.79	0.00
Vive - IMU	V_low	H_far	14.78	1.07	5004.05	13.76	0.00
Optical - Vive	V_mid	H_far	1.50	1.07	5004.00	1.40	0.50
Optical - IMU	V_mid	H_far	0.14	1.07	5004.00	0.13	1.00
Vive - IMU	V_mid	H_far	-1.36	1.07	5004.00	-1.27	0.58
Optical - Vive	V_high	H_mid	-2.70	1.07	5004.00	-2.53	0.06
Optical - IMU	V_high	H_mid	-0.99	1.07	5004.00	-0.93	0.79
Vive - IMU	V_high	H_mid	1.70	1.07	5004.00	1.60	0.38
Optical - Vive	V_low	H_mid	-10.94	1.08	5004.00	-10.13	0.00
Optical - IMU	V_low	H_mid	4.98	1.07	5004.05	4.64	0.00

Vive - IMU	V_low	H_mid	15.92	1.07	5004.05	14.82	0.00
Optical - Vive	V_mid	H_mid	-6.16	1.07	5004.00	-5.76	0.00
Optical - IMU	V_mid	H_mid	-4.11	1.07	5004.00	-3.85	0.00
Vive - IMU	V_mid	H_mid	2.05	1.07	5004.00	1.92	0.22

Table 6. Pairwise Comparisons between Systems for Shoulder Flexion Angle

contrast	*H Target*	*V Target*	*estimate*	*SE*	*df*	*t.ratio*	*p.value*
Optical - Vive	H_close	V_high	-5.78	4.61	23.25	-1.25	0.60
Optical - IMU	H_close	V_high	15.77	4.40	24.42	3.59	0.01
Vive - IMU	H_close	V_high	21.55	3.84	29.29	5.62	0.00
Optical - Vive	H_far	V_high	-0.40	4.61	23.25	-0.09	1.00
Optical - IMU	H_far	V_high	20.75	4.40	24.42	4.72	0.00
Vive - IMU	H_far	V_high	21.15	3.84	29.29	5.51	0.00
Optical - Vive	H_mid	V_high	-2.58	4.61	23.25	-0.56	0.94
Optical - IMU	H_mid	V_high	14.63	4.40	24.42	3.33	0.01
Vive - IMU	H_mid	V_high	17.21	3.84	29.29	4.49	0.00
Optical - Vive	H_close	V_low	-0.25	4.62	23.47	-0.05	1.00
Optical - IMU	H_close	V_low	7.40	4.41	24.55	1.68	0.36
Vive - IMU	H_close	V_low	7.65	3.84	29.50	1.99	0.21
Optical - Vive	H_far	V_low	-17.22	4.62	23.47	-3.72	0.01
Optical - IMU	H_far	V_low	22.42	4.41	24.55	5.09	0.00
Vive - IMU	H_far	V_low	39.64	3.84	29.50	10.31	0.00
Optical - Vive	H_mid	V_low	-10.63	4.62	23.47	-2.30	0.13
Optical - IMU	H_mid	V_low	10.66	4.41	24.55	2.42	0.10
Vive - IMU	H_mid	V_low	21.29	3.84	29.50	5.54	0.00

Optical - Vive	H_close	V_mid	-8.57	4.61	23.25	-1.86	0.27
Optical - IMU	H_close	V_mid	4.34	4.40	24.42	0.99	0.76
Vive - IMU	H_close	V_mid	12.91	3.84	29.29	3.36	0.01
Optical - Vive	H_far	V_mid	-7.08	4.61	23.25	-1.53	0.43
Optical - IMU	H_far	V_mid	16.53	4.40	24.42	3.76	0.00
Vive - IMU	H_far	V_mid	23.60	3.84	29.29	6.15	0.00
Optical - Vive	H_mid	V_mid	-3.69	4.61	23.25	-0.80	0.85
Optical - IMU	H_mid	V_mid	4.97	4.40	24.42	1.13	0.68
Vive - IMU	H_mid	V_mid	8.65	3.84	29.29	2.26	0.13

Table 7. Pairwise Comparisons between Systems for Elbow Flexion Angle

contrast	*H Target*	*L Target*	*estimate*	*SE*	*df*	*t.ratio*	*p.value*
Optical - Vive	H_close	L_left	-15.29	4.55	21.00	-3.36	0.01
Optical - IMU	H_close	L_left	6.31	4.65	20.67	1.36	0.54
Vive - IMU	H_close	L_left	21.60	5.94	18.14	3.64	0.01
Optical - Vive	H_far	L_left	0.50	4.55	21.00	0.11	1.00
Optical - IMU	H_far	L_left	-5.29	4.65	20.67	-1.14	0.67
Vive - IMU	H_far	L_left	-5.79	5.94	18.14	-0.98	0.77
Optical - Vive	H_mid	L_left	1.27	4.55	21.00	0.28	0.99
Optical - IMU	H_mid	L_left	4.59	4.65	20.67	0.99	0.76
Vive - IMU	H_mid	L_left	3.31	5.94	18.14	0.56	0.94
Optical - Vive	H_close	L_mid	-26.03	4.55	21.00	-5.72	0.00
Optical - IMU	H_close	L_mid	6.67	4.65	20.67	1.44	0.49
Vive - IMU	H_close	L_mid	32.71	5.94	18.14	5.51	0.00
Optical - Vive	H_far	L_mid	2.37	4.55	21.00	0.52	0.95

Optical - IMU	H_far	L_mid	-0.90	4.65	20.67	-0.19	1.00
Vive - IMU	H_far	L_mid	-3.26	5.94	18.14	-0.55	0.95
Optical - Vive	H_mid	L_mid	-8.29	4.55	21.00	-1.82	0.29
Optical - IMU	H_mid	L_mid	8.67	4.65	20.67	1.87	0.27
Vive - IMU	H_mid	L_mid	16.96	5.94	18.14	2.86	0.05
Optical - Vive	H_close	L_right	-19.36	4.55	21.00	-4.25	0.00
Optical - IMU	H_close	L_right	2.03	4.65	20.67	0.44	0.97
Vive - IMU	H_close	L_right	21.39	5.94	18.14	3.60	0.01
Optical - Vive	H_far	L_right	0.92	4.55	21.00	0.20	1.00
Optical - IMU	H_far	L_right	-9.34	4.65	20.67	-2.01	0.22
Vive - IMU	H_far	L_right	-10.26	5.94	18.14	-1.73	0.34
Optical - Vive	H_mid	L_right	-4.87	4.55	21.00	-1.07	0.71
Optical - IMU	H_mid	L_right	-2.34	4.65	20.67	-0.50	0.96
Vive - IMU	H_mid	L_right	2.53	5.94	18.14	0.43	0.97