Model Based Work Assessment: Combining Spatial and Temporal Modeling for Structured Proactive Work Analysis

By

Yifan Li

A dissertation submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy
(Industrial and Operations Engineering)
In the University of Michigan
2024

Doctoral Committee:

Professor Thomas J. Armstrong, Chair
Professor Toni C. Antonucci
Associate Professor Bernard Martin
Associate Professor Leia Stirling

Yifan Li

lyifan@umich.edu

ORCID ID: 0000-0003-0850-9007

DEDICATION

To my parents, Wenhua Wu and Jun Li.

To my grandparents, 吴兴国, 蒋艳云, 李富生, and 杜听凤

ACKNOWLEDGEMENTS

First and foremost, I wish to express immense gratitude for my advisor, Dr. Thomas Armstrong. He not only “adopted” me after my initial advisor left Michigan, but also guided me through some very difficult times. Thank you for your flexibility and patience throughout the COVID pandemic. You have been a wonderful mentor both for my PhD, as well as guiding me through how to teach and interact with students. Your numerous years of experience was invaluable, and I just hope I was able to take away a fraction of your expertise.

I would also like to thank all of my committee members. Dr. Bernard Martin – you have always been a steady presence in the department, and I will always think fondly of the times we struggled with the force plates together. Dr. Leia Stirling – you constantly made sure that I (along with all the other Center for Ergonomics students) were on track and being fully supported. And Dr. Toni Antonucci – my later work regarding worker wellness and the future of work would not be the same without your inspirations.

I was very very fortunate to have financial support from the National Institute of Occupational Safety and Health Traineeship Program. Not only did it help move my research along, it also allowed me to gain breadth in understanding broader impacts on worker health that I hope to take into my career in the future.

I would also like to acknowledge Dr. Sheryl Ulin and the Consultation Education and Training (CET) Grant awarded by the Michigan Occupational Safety and Health Administration (MIOSHA). This allowed me to perform my analysis using prior data sets.

To all of my friends and colleagues in the department – Dr. Justin Haney, Dr. Sol Lim, Dr. Yadriana Acosta-Sojo, Dr. Karanvir Panesar, Dr. Kam Tabattanon, Dr. Taa Soratana, Patrik Schuler, Dr. Yidu Liu, Dr. Du Na, Dr. Yuzhi Wan, Kirk Wang, and Nick Sandhu – thanks for all the laughs and tears together.

I also want to thank all of the support from the department – Chuck Wooley, Eyvind Claxton, Olof (Mint) Minto, Matt Irelan, Tina Picano Sroka, and Dr. Paul Greene – without you guys, the department would not run as well and I was lucky enough to work with each and every one of you!

Lastly, I want to thank my friends and family for always supporting me through the ups and downs of this massive endeavor. I could not do it without you guys!

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF APPENDICES

ABSTRACT

Localized fatigue is a common phenomenon experienced in a variety of workplaces and is commonly associated as a harbinger for chronic work-related musculoskeletal disorders (WMSDs). Thus, workload management and various work assessment techniques have been introduced to understand how the human worker is responding to the various exposures happening in the workspace. These tools commonly rely on worker self-reporting, having an expert observer and evaluate the job itself, or to have direct measurements of worker physiologic response. Self-reporting tools, while useful for capturing a snapshot, are very susceptible to bias, and also lack context. Many observer-based measurements can vary depending on the observer, or on the individual that is observed. Small differences in what the observer sees, or what the worker performs can have a drastic impact on the observed scores. In addition, many past studies have demonstrated that minute differences in the timing of the work pattern, as well as the workspace layout can cause a significant change in the physiologic responses within an individual. Lastly, direct physiologic tools have a lot of potential in quantifying and understanding the response happening within the worker; however, a lot of times context of the work itself is missing.

Thus, this dissertation proposes a formalized Model-Based Work Assessment Framework that builds up spatial and temporal relationships between the worker and their

work from the context of work standards. By using the work goals and work standards as an input, additional rigor, and context of the exposures from different movement patterns can be understood.

CHAPTER 1

Introduction

1.1 Problem Statement:

Localized fatigue is a common and significant problem for workers involved in repetitive work across many industries and different types of work tasks. Localized fatigue is also a precursor of chronic musculoskeletal disorders (MSDs); when attributing factors of fatigue and MSDs arise at work, these disorders are then specifically classified as Work-Related Musculoskeletal Disorders (WMSDs). This thesis proposes that implementing a spatial-temporal model of the worker-work interaction based on standardized work can provide a rigorous framework for understanding, designing for, and controlling ergonomic work stresses. A spatial-temporal model can also be used together with ergonomic analysis tools for a broad range of work activities and work domains.

Many tools currently exist to assess fatigue and potential WMSDs risk and generally fall into one of three bins: self-reporting, observation based, and physiological response measurements. While self-reporting tools do typically paint a good picture of experienced and perceived fatigue, self-reporting tools often lack context of why an individual is experiencing discomfort. Some observational tools commonly used in the field – Rapid Upper Limb Assessment (RULA), Strain Index, Occupational Repetitive Actions (OCRA), and American Conference of Governmental Industrial Hygienists defined Threshold Limit Values (ACGIH TLVs) - are all generally based on understanding an exposure-response model where the risk of WMSDs increases with increasing duration or magnitude of exposure to biomechanical loads (Kong et al., 2018; Dempsey et al., 2019). However, biomechanical loads can vary subtly based on differing work settings, work tools, work habits, and workers themselves. Thus, results can vary a lot from observer to observer, from worker to worker. Observation based analysis is also based on existing work methods and can miss factors such as work process, equipment, materials, conditions, and worker differences.

There are also a growing number of tools based on collecting physiological or biomechanical data to quantify human responses (such as computer vision, wearable IMUs, EMG, fNIR, HRV, etc) that make it possible to study selected risk factors over space and time that were heretofore possible (Lim et al., 2020). These methods can directly provide information about postures and movements and other physiological responses. These methods don’t explain what it is about the job that causes a stressful posture, e.g., the height of a workbench, the placement of the materials, the length of a tool, etc. They don’t explain why a worker’s hand may be moving between two locations once every 5 seconds or once every minute, that might be obvious with knowledge of the production process and work standard. As the use of these new technologies grows, it becomes increasingly important that we understand the relationship between biomechanical load patterns and underlying work factors to interpret those data.

For a more rigorous work assessment process and applying various assessment tools, an underlying model is needed that establishes possible ranges for job/task factors that affect ergonomic stresses. This dissertation is concerned with the development of a framework that combines the use of spatial and temporal models for determining the biomechanical load patterns related to risk of fatigue and chronic musculoskeletal disorders.

1.2 Background:

1.2.1 Fatigue and WMSDs

Historically, Localized Fatigue has always been considered as a precursor or a harbinger for Musculoskeletal disorders (MSDs) (Armstrong et al., 1993). MSDs are specific issues that arise within the muscle, tendon, joints, soft tissues, and/or nerve (Chaffin, 1973; Gallagher et al., 2017; Hagberg et al., 1984). These may manifest from discomfort to pain, and even be debilitating for day-to-day lives. These MSDs may be caused or exacerbated by individual factors, work-related factors, or a combination of both (Gerard et al., 2001). When specifically focusing on work contributions to the causes or exacerbation of MSDs, it is typically referred to as Work-Related Musculoskeletal disorders (WMSDs) (Armstrong et al., 1986). Localized fatigue in of itself is not of a huge detriment - in fact, we commonly experience fatigue as a normal part of day-to-day lives. However, the human system must be given sufficient time to recover and rest. When inadequate rest is given, that is when fatigue becomes chronic, and could start negatively impacting an individual both during and outside of work (Gallagher et al., 2017; Armstrong et al., 1993). The cause of Localized Fatigue is often caused by the work requirements and demands exceeding the capabilities of a worker. By itself, any exposure to external factors does not necessarily have a negative impact on a given worker (internal system). However, if the dosage of the exposure of physical exertion is high enough, and the worker can't adapt and respond appropriately as limited by their physiological and biological capabilities, then they are at risk for long term WMSDs (Armstrong et al., 1993). A lot of these most work-related factors for localized fatigue include: long periods of sedentary work, repetitive motions, and sustained postures. These demands, coupled with the increasing pace of work and production pressures, contribute to a heightened risk of WMSDs.

1.2.2 WMSDs Measurement Tools & Gaps

A number of tools are used to score and manage the risk of localized musculoskeletal disorders, MSDs. These tools typically fall under a few bins - self-reporting, observation based, and biomechanical modeling. Common and popular self-assessment tools include the Nordic Musculoskeletal Questionnaire (NMQ), Quick Exposure Checklist (QEC), and NASA TLX (Crawford, 2007; David et al., 2008; Hart, 2006). While these tools can capture a snapshot of how the individual is perceiving fatigue or pain, they lack contextualization within the interaction between the worker and the work and often differ than observations from experts (Spielholz et al., 2001).

The most popular methods of evaluating for WMSDS are observational based where experts are brought in the workplace and analyze for risk using various measures of repetition, force, and posture (Kong et al. 2018; Jones, 2010). Some of the more commonly used tools in the field include: OCRA, RULA, Rapid Entire Body Assessment (REBA), Strain Index, ACGIH TLV, Ovako Working Posture Analyzing System (OWAS), and Rapid Office Strain Assessment (ROSA) (Occhipinti, 1998; Colombini, 1998; McAtamney & Corlett, 1993; Hignett and McAtamney, 2000; Moore and Garg, 1995; Rempel, 2018; Karhu, Kansi et al., 1977; Karhu, Harkonen et al., 1981; Sonne et al., 2012). These are based on an underlying exposure-response model in which the risk of MSDs increases with increasing dosage to physical loads (Armstrong 1996). Biomechanical loads result from movements and exertions of the body that are required to do a job; as a result load patterns can differ greatly among different industries, different work settings, different tools, and different workers (Latko et al., 1997). Biomechanical loads can also vary significantly over space within one job due to subtle and not so subtle differences related to the placement of equipment and materials, or the condition of tools. Differences may occur over time along with the condition of tools and equipment or individual worker preferences. These differences help to explain some of the underlying differences among various tools for determining WMSD risk but also differences in risk scores when the same tools are used for what on the surface appears to be the same job (Ulin et al., 1990).

Lastly, there are many direct measurement techniques that can be used to quantify for physical measures and responses such as: computer vision tools for movement patterns, wearable sensing to quantify for movement and/or physiological responses (heart rate, breathing patterns, etc) (Lim et al., 2020; Yu et al., 2019). However, a lot of these measurements are not grounded in an understanding of the relationship between the worker and the work.

This brings us to the existing gaps in the literature. While there exists a lot of methods to quantify exposures, they are either observer based, which introduces observational bias. Or they are done without sufficient context for the work that is being performed. Thus, a deeper understanding of the various spatial and temporal factors is needed to construct a robust model.

1.2.3 WMSDs and Spatial Factors

One of the first aspects of job and workspace design in regard to the relationship between the worker and the workspace is the physical interactions and the potential ranges of distances and spaces to accommodate for individual differences. This is commonly done using anthropometry and modeling reach and body sizes across the range of a population (Garneau and Parkinson, 2009; Drillis and Contini, 1966). However, this does not directly shed light to the impact of varying the dimensions of the workspace or workspace layouts in a dynamic setting. The spatial layout of the workspace is a determining factor for how the worker interacts with their environment and different configurations of space changes posture, reach locations and distances, which in turn changes the underlying doses experienced by the worker's physiological systems (Armstrong et al., 1993). While there has been much work quantifying the impact of changing loads and work distances on biomechanical load, not much literature exists to predict biomechanical load directly from workspace models. For example, varying dimensions within a job space directly impacts reach distances and reach postures, ultimately impacting the load patterns and task performance times in even simple tasks such as manipulating cards (Yasukouchi et al., 1993). For office work, positioning of work peripherals and the relative spatial relationships between the worker and the work desk, and keyboards all been shown to be related to fatigue, demonstrating the importance of identifying spatial layout patterns in our tool (Huang, 1999). Furthermore, in work tasks that require the use of hand tools, the target location of work objects can directly affect the body posture, impacting the overall biomechanical load experienced by the worker

(Armstrong et al., 1986; Ulin et al., 1993). This work aims to offer a preemptive methodology to analyze the effect of varying workspace layout on biomechanical load patterns.

1.2.4 WMSDs and Temporal factors

Physically changing the load experienced by an individual have been shown to play a significant role in worker productivity, muscle fatigue, and worker discomfort; however, just as important, there are also key temporal factors that impact the worker include the pace of work, how long an individual has been working, and break and rest patterns of the worker (Wells et al., 2007; Rohmert, 1973; Potvin, 2012; Karasek, 1979). However, temporal factors and dynamic work cycle patterns are still aspects not included in many of the commonly used observation methods (David, 2005). The driving factors for temporal relationships in work are physiological responses and how fast individuals' physiological systems can recover from work. This concept was formalized in the Dose-Response model; work standards and requirements determine the type of movement required by the muscle, and in turn disturbs the internal state of the individuals (Armstrong et al., 1993). To build up a model of the temporal work patterns of an individual, the work standards (duration and types of tasks) for a worker's day must be established. Key details of breaks are also important to capture as it directly impacts the amount of recovery time an individual has compared to the work times; higher duty cycle times are often associated with increased localized fatigue (Armstrong et al., 2003; Latko et al., 1999; Silverstein et al., 1986). Intermittent breaks have proven beneficial for worker fatigue (Claudon et al., 2020; Potvin, 2012; Mathiassen & Winkel, 1991; ACGIH 2018).

Lastly, postural information and how individuals hold themselves can change the required force for a given task due to changing the relevant kinematic chain (Armstrong et al., 1986).

1.2.5 Model development

Biomechanical loads occur when forces are exerted to see, reach for, grasp or manipulate a work object. The relationship between an assessment score for WMSDs and fatigue, load patterns, and work and worker factors can be summarized as shown in Figure 1.1.

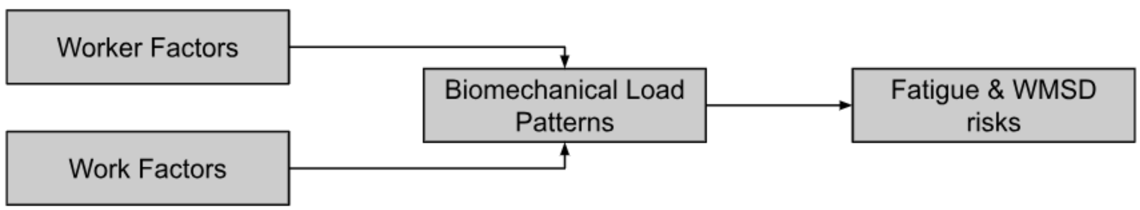


Figure 1.1: Worker & work interaction defines biomechanical load patterns which can result in an assessment score for WMSD and fatigue risk

Loads on major joints such as the wrist, elbow, shoulder, neck, and back are related to gravity and inertial forces acting on objects held in the hand or on the body. Loads are related to work design and worker behavior factors and can be estimated from observations of postures and exertions as a worker performs a job. Loads also can be estimated from computations based on the size, weight, and shape of the worker objects and based on the spatial relationship between the worker and the work. The spatial relationship between the worker and work is related to equipment used, its size and placement, to the placement and presentation of materials, to the size and placement of the worker, and to the work method. These factors also determine the time required to get and move objects from one location to another.

A model can be constructed prospectively based on available work standards, equipment specifications, material specifications, and workspace layout. The work standards data may include Takt times, work quantity, completion standards, and special details about how the products are handled (fragile, cryogenic, etc). The work equipment includes the manufacturer and model number and settings related to speed or force. Tools should include protective equipment (gloves, eye protection, respiratory protection, etc). Materials may include physical objects that become part of an assembly, liquids, powders, or gasses that are mixed to produce a product; biological living or not living, The materials include information about the shape, size, and weight and factors affecting how the object is handled (sharp edges, biohazard, sterile, frozen, etc.).

A model of the spatial relationship between the worker and work can be a simple sketch of key dimensions that affect the posture required to see, get, or use work objects. Alternatively, these models can be a CAD model created using any one of a number of widely used CAD programs; examples include AutoCAD, Siemens, and CATIA. In many cases, it will be found that these models already exist and were used in the original job setup. Many manufacturers make CAD models of their equipment freely available so that they can be imported into workstation models. Postures and biomechanical loads can be computed using specialized software such as 3DSSPP (Chaffin, 2005). Alternatively, simple stick figures based on anthropometry of the anticipated workers also can be used to estimate postures.

A model of the temporal aspects of the job can be created using the CAD model to determine move distances and predetermined time systems, Predetermined Time Systems (PTSs), to determine the normal time for qualified and trained workers to complete each action under normal conditions. PTSs are widely used in manufacturing settings to determine production times, allocate work, balance assembly lines, and estimate labor costs. Examples include Work Factor, MTM, MOST, and MODAPTS (Freivalds and Niebel, 2013). A framework is proposed that can integrate various existing tools - CAD modeling to determine spatial relationships, Predetermined time systems (PTS) to determine temporal relationships, and ergonomic tools to determine load patterns - in a formalized work assessment method.

For the purposes of this discussion, we will focus on the ACGIH TLV® for localized fatigue. Although localized fatigue is considered a transient phenomenon, it is a major cause of discomfort that interferes with worker performance. Localized fatigue is an important problem in its own right, but also is a likely precursor or at least a harbinger of chronic MSDs. Both localized fatigue and MSDs occur when a biomechanical load pattern does not include sufficient recovery. Additionally, we will focus primarily on hand and forearm fatigue, but the concepts and applications are generalizable to other parts of the body such as the elbows, shoulders, and back. Using a spatial-temporal approach, a new model was developed and is shown in Figure 1.2. The top path of this model takes a Model-based approach, using various information about the work and worker to develop a fatigue model; the bottom path take a traditional observer-based approach.

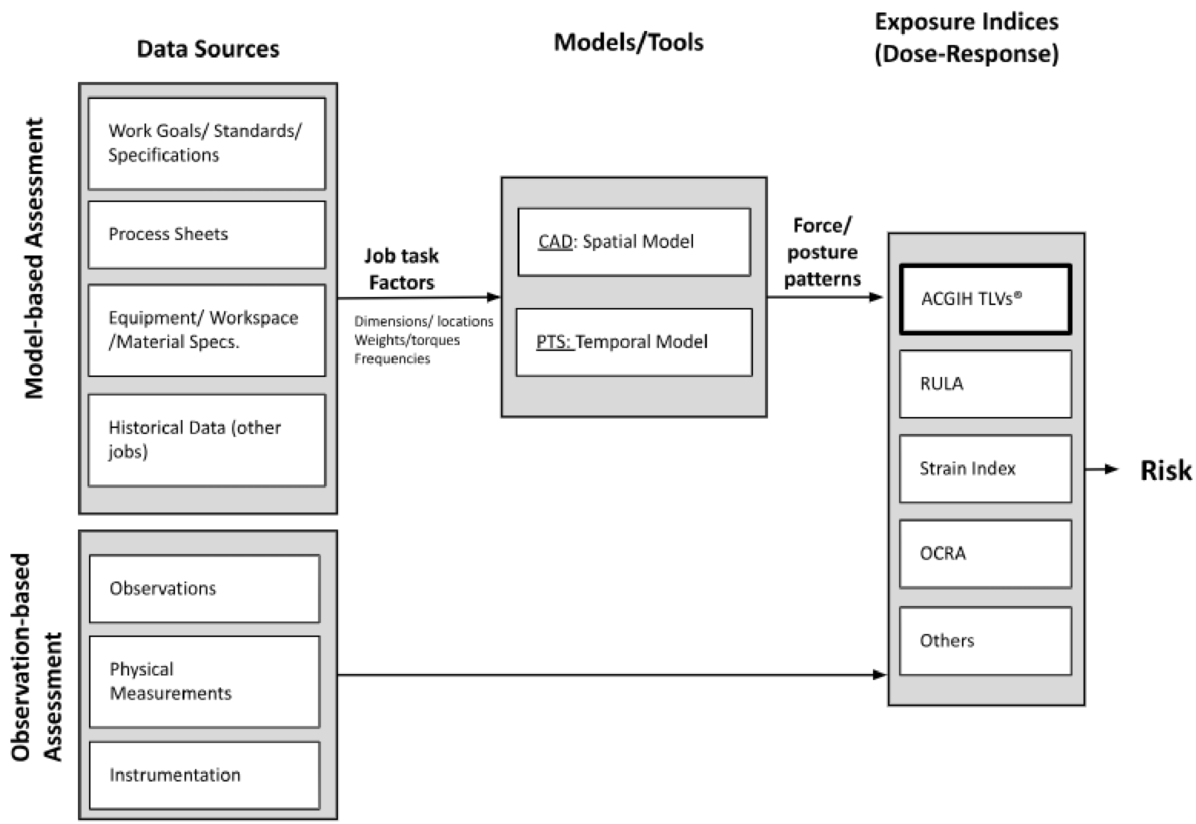


Figure 1.2: Full Model-based Work Assessment Framework built from data sources focusing on work

1.3 Research objectives

The goal of this dissertation is to formulate, establish, and implement a Model-Based Work Assessment (MBWA) Framework that can be proactively applied for human-centered work and job design. There are three key objectives associated with this dissertation:

The first objective is to demonstrate the applications of the Model-Based Work Assessment (MBWA) framework as compared to traditional time-study techniques. This will be done in the context of various work and job tasks through combining spatial and temporal modeling. This will also provide contextual understanding of the underlying work goals driving movement patterns.

The second objective is to incorporate ergonomic dose-response risk factors as compared to traditional observational methods. This will also demonstrate the strength and flexibility of the framework application by proactively suggesting workflow changes, acting as a “decision support system” during the work-design phase for industries (Womack et al., 2005).

The last objective is to apply the framework to less structured work and to show that applying spatial and temporal modeling of a job can provide context to work necessities and that the framework can be applied in various work settings.

1.4 Dissertation Organization:

This dissertation contains five chapters and six appendices. Chapter one introduces and builds up the Model-based Work Assessment (MBWA) framework as well as the scope of the work.

Chapter two demonstrates the application and validity of incorporating Spatial & temporal modeling of various industry jobs in comparison to traditional time-study approaches. Spatial models using CAD and temporal models using MODAPTS were incorporated, and cycle times were produced using the model.

Chapter three builds on the work from chapter two incorporates exposure-dose risk estimation. The same jobs from Chapter two were further analyzed and exertion patterns were examined using both the Model-based approach, and traditional observational methods. This chapter also demonstrates the proactive nature of applying the framework, offering examples of workflow changes to reduce worker exposure.

Chapter four explores the application of the framework in non-traditional work settings. The MBWA framework was used to develop an online Remote Self-assessment Tool (REST) for Work from Home (WFH) workers. A mixed-method approach involving a focus group was leveraged to understand the strengths and weaknesses of the first iteration of the REST tool.

Lastly, chapter five summarizes the results, key contributions, and broader impacts of this framework. Chapter five also explores future applications of this framework and other domains for continuing research.

References

Armstrong, T. J., Radwin, R. G., Hansen, D. J., & Kennedy, K. W. (1986). Repetitive trauma disorders: job evaluation and design. Human factors, 28(3), 325-336.

Armstrong, T. J., Buckle, P., Fine, L. J., Hagberg, M., Jonsson, B., Kilbom, A., ... & Viikari-Juntura, E. R. (1993). A conceptual model for work-related neck and upper-limb musculoskeletal disorders. Scandinavian journal of work, environment & health, 73-84.

Armstrong, T., W. M. Keyserling, D. C. Grieshaber, M. Ebersol and E. Lo (2003). Time based job analysis for control of work related musculoskeletal disorders. 15th triennial Congress of the International Ergonomics Association, Seoul, Korea.

Chaffin, D. B. (1973). Localized muscle fatigue—definition and measurement. Journal of Occupational and Environmental Medicine, 15(4), 346-354.

Chaffin, D. B. (2005). 3D SSPP (Static Strength Prediction Program), version 5.04. Ann Arbor (MI): University of Michigan.

Claudon, L., Desbrosses, K., Gilles, M. A., Pichené-Houard, A., Remy, O., & Wild, P. (2020). Temporal leeway: can it help to reduce biomechanical load for older workers performing repetitive light assembly tasks?. Applied Ergonomics, 86, 103081.

Colombini, D. (1998). "An observational method for classifying exposure to repetitive movements of the upper limbs." Ergonomics 41(9): 1261-89.

Crawford, J. O. (2007). The Nordic musculoskeletal questionnaire. Occupational medicine, 57(4), 300-301.

David, G. C. (2005). Ergonomic methods for assessing exposure to risk factors for work-related musculoskeletal disorders. Occupational medicine, 55(3), 190-199.

David, G., Woods, V., Li, G., & Buckle, P. (2008). The development of the Quick Exposure Check (QEC) for assessing exposure to risk factors for work-related musculoskeletal disorders. Applied ergonomics, 39(1), 57-69.

Dempsey, P. G., Lowe, B. D., & Jones, E. (2019). An international survey of tools and methods used by certified ergonomics professionals. In Proceedings of the 20th Congress of the International Ergonomics Association (IEA 2018) Volume III: Musculoskeletal Disorders 20 (pp. 223-230). Springer International Publishing.

Drillis, R., Contini, R., & Bluestein, M. (1964). Body segment parameters. Artificial limbs, 8(1), 44-66.

Freivalds, A., & Niebel, B. (2013). Niebel's Methods, Standards, & Work Design. McGraw-Hill higher education

Gallagher S, Schall Jr MC. Musculoskeletal disorders as a fatigue failure process: evidence, implications and research needs. Ergonomics. 2017;60(2):255-69.

Garneau, C. J., & Parkinson, M. B. (2009). Including preference in anthropometry-driven models for design.

Gerard, M. J., Armstrong, T. J., Martin, B. J., & Rempel, D. M. (2001). The effects of work pace on intra-subject and inter-subject keying force, electromyography, and fatigue. Hum. Factors.

Hagberg, M., & Kvarnström, S. (1984). Muscular endurance and electromyographic fatigue in myofascial shoulder pain. Archives of physical medicine and rehabilitation, 65(9), 522-525.

Hart, S. G. (2006, October). NASA-task load index (NASA-TLX); 20 years later. In Proceedings of the human factors and ergonomics society annual meeting (Vol. 50, No. 9, pp. 904-908). Sage CA: Los Angeles, CA: Sage publications.

Hignett, S. and L. McAtamney (2000). "Rapid entire body assessment (REBA)." Applied Ergonomics 31(2): 201-5.

Huang, I. W. (1999). Effects of keyboards, armrests, and alternating keying positions on subjective discomfort and preferences among data entry operators. University of Michigan.

Karasek Jr, R. A. (1979). Job demands, job decision latitude, and mental strain: Implications for job redesign. Administrative science quarterly, 285-308.

Karhu, O., P. Kansi, et al. (1977). "Correcting working postures in industry: A practical method for analysis." Applied Ergonomics 8: 199-201.

Karhu, O., Härkönen, R., Sorvali, P., & Vepsäläinen, P. (1981). Observing working postures in industry: Examples of OWAS application. Applied ergonomics, 12(1), 13-17.

Kong, Y. K., Lee, S. Y., Lee, K. S., & Kim, D. M. (2018). Comparisons of ergonomic evaluation tools (ALLA, RULA, REBA and OWAS) for farm work. International journal of occupational safety and ergonomics, 24(2), 218-223.

Latko, W. A., Armstrong, T. J., Franzblau, A., Ulin, S. S., Werner, R. A., & Albers, J. W. (1999). Cross-sectional study of the relationship between repetitive work and the prevalence of upper limb musculoskeletal disorders. American journal of industrial medicine, 36(2), 248-259.

Latko, W. A., T. J. Armstrong, et al. (1997). "Development and evaluation of an observational method for assessing repetition in hand tasks." Am Ind Hyg Assoc J 58(4): 278-85.

Lim, S., & D'Souza, C. (2020). A narrative review on contemporary and emerging uses of inertial sensing in occupational ergonomics. International journal of industrial ergonomics, 76, 102937.

Mathiassen, S. E., & Winkel, J. (1991). Quantifying variation in physical load using exposure-vs-time data. Ergonomics, 34(12), 1455-1468.

McAtamney, L., & Corlett, E. N. (1993). RULA: a survey method for the investigation of work-related upper limb disorders. Applied ergonomics, 24(2), 91-99.

Moore, J. S. and A. Garg (1995). "The Strain Index: a proposed method to analyze jobs for risk of distal upper extremity disorders." Am Ind Hyg Assoc J 56(5): 443-58.

Occhipinti, E. (1998). OCRA: a concise index for the assessment of exposure to repetitive movements of the upper limbs. Ergonomics, 41(9), 1290-1311.

Potvin, J. R. (2012). Predicting maximum acceptable efforts for repetitive tasks: an equation based on duty cycle. Human factors, 54(2), 175-188.

Rempel, D. (2018). 1631c Recent changes to the ACGIH hand activity level TLV.

Rohmert, W. (1973). Problems of determination of rest allowances Part 2: Determining rest allowances in different human tasks. Applied ergonomics, 4(3), 158-162.

Silverstein, B. A., Fine, L. J., & Armstrong, T. J. (1986). Hand wrist cumulative trauma disorders in industry. Occupational and Environmental Medicine, 43(11), 779-784.

Sonne, M., Villalta, D. L., & Andrews, D. M. (2012a). Development and evaluation of an office ergonomic risk checklist: ROSA–Rapid office strain assessment. Applied ergonomics, 43(1), 98-108.

Spielholz, P., Silverstein, B., Morgan, M., Checkoway, H., & Kaufman, J. (2001). Comparison of self-report, video observation and direct measurement methods for upper extremity musculoskeletal disorder physical risk factors. Ergonomics, 44(6), 588-613.

Ulin, S. S., Armstrong, T. J., Snook, S. H., & Monroe-Keyserling, W. (1993). Examination of the effect of tool mass and work postures on perceived exertion for a screw driving task. International Journal of Industrial Ergonomics, 12(1-2), 105-115.

Ulin, S. S., Ways, C. M., Armstrong, T. J., & Snook, S. H. (1990). Perceived exertion and discomfort versus work height with a pistol-shaped screwdriver. American Industrial Hygiene Association Journal, 51(11), 588-594.

Wells, R., Mathiassen, S. E., Medbo, L., & Winkel, J. (2007). Time—a key issue for musculoskeletal health and manufacturing. Applied Ergonomics, 38(6), 733-744.

Womack, S. K., & Armstrong, T. J. (2005). Use of a computerized decision support system for primary and secondary prevention of work-related MSD disability. Journal of occupational rehabilitation, 15, 313-328.

YASUKOUCHI, A., ARAI, K., OHASHI, J., SAKO, H., & KAT, K. (1993). Effects of the Directlon and Distance of Horizontal Arm Movements on Local Muscular Strain: A Fundamental Study on the Teller Workplace in Bank. The Annals of physiological anthropology, 12(6), 341-350.

Yu, D., Antonik, C. W., Webber, F., Watz, E., & Bennett, W. (2019). Multi-modal physiological sensing approach for distinguishing high workload events in remotely piloted aircraft simulation. Human-Intelligent Systems Integration, 1, 89-99.

CHAPTER 2

Model Based Work Assessment: Combining Computer Aided Design and Predetermined Time Systems for Time Study Analysis

Abstract:

This work aims to demonstrate the use of CAD-based workplace models that describe the spatial relationships of a given job and the use with Predetermined Time Systems (PTS) - namely MODAPTS - in lieu of traditional time studies. Traditional work assessment methods either utilize self-reporting, observer-based metrics, or direct measurements of physiological response. A lot of these methods are dependent on the nature of the work itself; but these methods lack context for understanding the fundamental nature of the work. By building up a Model-Based Framework, work assessment can be done as an input of the task requirements, adding rigor and context to understanding the work-worker relationship. AutoCAD was chosen for spatial modeling of the workspace, and MODAPTS was chosen for the temporal modeling. This work shows that CAD and PTS models can be combined in an underlying model for predicting work time and work methods that can then be used for interpreting various fatigue risks. It also gives insight on where MODAPTS categorization of movement patterns falls short and provides taxonomy updates so that a model-based approach can more accurately reflect the job. This work provides a framework that can serve as a foundation for

interpreting observation-based results, for identifying specific risk factors, and for designing engineering interventions.

2.1 Introduction

The key objectives of this work are: (1) Development and application of Model-Based Work Assessment Framework which links together the existing concepts of workspace modeling and predetermined time systems. (2) Evaluate usage of Model-Based Work Assessment Framework versus traditional time study methods to assess for accuracy as well as propose taxonomy updates in use cases with large discrepancies between framework results and time study results.

2.1.1 WMSDs and Assessment Methods

Localized fatigue is a common issue for workers engaged in repetitive work; it also is regarded as a precursor of work-related musculoskeletal disorders (WMSDs) (Armstrong, 2021; Armstrong, 2023). There have been correlations shown that longer durations of work in a given day is directly linked to physiological spikes in fatigue (Mathiassen, 1996; Wells, 2007). These repetitive movements coupled with extended periods of localized fatigue often precede more serious and chronic work-related musculoskeletal disorders, WMSDs (Barr, 2004). With WMSD being a persistent issue in many work areas there is a need to understand the underlying load patterns that lead to localized fatigue (Bernard et al., 1997).

Numerous tools have been proposed for assessing fatigue and WMSD risk based on posture and force patterns, e.g., RULA, Strain Index, OCRA, and ACGIH TLV®s (Kong et al. 2018; Jones, 2010). However, while these tools include select movement and force patterns, there is a lack of holistic critical examination of the impacts of these patterns on the workers. Many of these tools are derived from the theories of standardized work. For any given work activity, it is theorized that there is one “best way” to perform a job - the standard work method (Taylor, 2004).

Standardized work methods have long been an area of study and focus for ergonomists and engineers alike, with researchers in the 1900s breaking down work tasks into sub steps and removing unnecessary motions (Gilbreth, 1911). With a growing emphasis on lean and optimized manufacturing, the focus for engineers is to understand the breakdown of each work task and how to optimize worker efficiency. This is seen in the specialization of workers and in assembly line work (Smith, 1863). Standardized work methods also allows for an easier quantification of motion patterns (spatial and temporal) for each worker; having standardized work cycles also makes studying exposure as a function of time feasible (Mathiassen, 1991). Even though most workplaces have adopted a more standardized approach to work practices, there still exists significant variability over space and time among ergonomics assessments as a result of even small variations in how materials and tools are laid out and in how individual workers perform the job. In order to study fatigue, an understanding of posture and force patterns are needed. In many cases, posture and force patterns are based on the observations of a small number of observers on a limited number of workers at different times and places. This could cause significant variation on the observed results. Thus, any observed result is a function of the standard work method and the sum of variation from the worker, observer, and work process.

This lends naturally for a need of an underlying model that can be used in a more rigorous analysis to identify sources of potential variations and also anticipate where differences may occur. A framework is proposed that can tie together various tools - CAD modeling to determine spatial relationships, Predetermined time systems (PTS) to determine temporal relationships, and the above listed ergonomic tools to determine load patterns - in a formalized work assessment method.

2.1.2 Predetermined Time Systems

Predetermined time systems (PTS) are used to systematically describe movement types and create a corresponding taxonomy assigning times to each movement type based on the movement's attributes. These PTS, such as MTM, MOST, and MODAPTS, are widely used to predict normal times as it allows for a larger work activity to be broken down into subtasks for analysis with each of these movements being independent of which worker is performing the task (Freivalds and Niebel, 2013; Cho, 2014). All of these time systems have been applied in industries - each having their own unique pros and cons. A common theme and drawback for these systems are the amount of training required (Takala, 2010). Of these, a popular and relatively easy to train system is MODAPTS, which looks at body motions that are required in a work task and how long each of those motions take (Freivalds and Goldberg, 1988). MODAPTS has been applied in a variety of industries - notably, it allows for a larger work activity to be broken down into subtasks for analysis and can show variations on how different workers approach the task (Cho, 2014).

MODAPTS can be expressed using two elements - the motion class (expressed using alphabetic symbols), and time values (expressed using numerals). MODAPTS classifies work elements based on type of motions. The “Move” class (M) focuses on movement of the upper limbs and trunk. The “Terminal” class uses two activities: Gets (G), for when workers are retrieving something, and Puts (P), for when a worker is releasing something. In addition, other auxiliary actions (such as reading or writing), and warehouse information are available to allow for complete and accurate coding of a specific task (MODAPTS, 2020; Heyde, 1983).

Traditionally, MODAPTS can be applied through observing worker movement patterns and distances of body parts moved. The distance of movement is often estimated or done through physical measurements. In recent years, work has also been done to apply the MODAPTS analysis through the use of motion tracking or wearable sensing suggesting that MODAPTS can indeed be performed accurately using only distances (Mallembakam, 2021; Wu, 2016). This work proposes that similar measurements of distances can be obtained through a virtual CAD model, and subsequently PTS can be used for estimations of work methods and patterns. This approach is laid out through the Model-Based Work Assessment (MBWA) Framework.

2.1.3 Spatial Models of Workspaces

Physical space modeling is an integral part of understanding load patterns experienced during a work task as even subtle differences in materials and workspace layout can impact exposures. While there has been much work quantifying the impact of changing loads and work distances on biomechanical load, not much literature exists to predict biomechanical load directly from workspace models. For example, varying dimensions within a job space directly impacts reach distances and reach postures, ultimately impacting the load patterns and task performance times in even simple tasks such as manipulating cards (Yasukouchi et al., 1993). Furthermore, in work tasks that require the use of hand tools, the target location of work objects can directly affect the body posture, impacting the overall biomechanical load experienced by the worker (Armstrong et al., 1986; Ulin et al., 1993). This work aims to offer a preemptive methodology to analyze the effect of varying workspace layout on work methods and work patterns. Thus, the first task is to recreate the workspace digitally. For this task, AutoCAD 2021 was chosen (while any number of CAD tools can be used).

2.2 Model Application

This work proposes a formalized framework - the Model-Based Work Assessment Framework (MBWA) - that can be applied for virtual job analysis (Figure 1.1). This framework utilizes CAD modeling and PTS modeling using inputs from work standards and is driven by contextualizing the work from a work goal point of view. This framework accentuates the differences between observation-based analysis and model-based. The top of the figure lays out the approach for Model-based Assessment. Initial data sources listed on the left feed in and inform the spatial and temporal models which act as intermediary tools which can then be used for exposure indices (such as ACGIH TLVs). This is in contrast to the traditional observation-based approach (bottom path of Figure 1.1) which uses observations, measurements (sometimes involving instrumentation) and calculates exposure indices directly. The Observation-based Assessment is done following existing methodologies (Armstrong, 2003).

2.3 Methods

The methodology for this work involved a combination of model generation based on existing jobs previously collected for ergonomic evaluation and training (Rabourn et al., 1996; Ulin et al., 2006); a total of five previous jobs were analyzed. These videos were chosen as they represent a number of different industries, hand movement patterns, hand loads, and walk patterns. To apply the framework, a spatial representation of the workspace was created. Movement patterns were derived using existing work descriptions. Then, a predetermined time system (MODAPTS) was used to characterize the resulting movement patterns.

2.3.1 Jobs Analyzed

The jobs were selected from a set of jobs which were published on the internet for ergonomics training by the Center For Ergonomics at the University of Michigan (Rabourn et al., 1996; Ulin et al., 2006). The availability of these videos were made possible through a Consultation Education and Training (CET) grant from the Michigan Occupational Safety and Health Administration (MIOSHA).

Table 2.1: Table of jobs analyzed for Study 1

Industry: Commercial clothing; **Job**: T-Shirt Printing; **Method**: 1) Step from printer to T-shirt cart; 2) Reach/grasp shirt from cart; 3) walk w/shirt to printer; 4) move/put shirt onto screen printer; 5) Position & smoothes shirt
Industry: Manufacturing; **Job**: Assembly Welding; **Method**: 1) Grasp two parts (brack & bolt) using each hand; 2) Reaches/grasp previous assembly from welder; 3) Put previous assembly to bin; 4) Put both parts on welder; 5) Reach and press activation buttons
Industry: Beverages; **Job**: Case stacking; **Method**: 1) Walk, reach, and grasp case of beverages from a rolling conveyor (variable location); 2) Lift, walk, and carry to pallet; 3) Position case on pallet (variable location)
Industry: Chemical; **Job**: Bottling Line; **Method**: 1) Turn, reach, and grasp case of bottles from pre-loading zone (constrained location); 2) Lift, turn, and position on pallet (variable location)
Industry: Food; **Job**: Case stacking; **Method**: 1) Walk, reach, and grasp two cases of material from pre-loading zone (constrained location); 2) Lift, walk, and carry to pallet; 3) Position case on pallet (variable location)

2.3.2 Spatial & Temporal Model

The analysis process involves first modeling the spatial relationship of the worker and the workstation. Following, a temporal model will be used with the existing spatial model as the basis. Generating spatial and temporal models can further be broken down into different steps: develop a sufficiently accurate virtual model of each job describing the workspace and work patterns through the use of CAD and develop a temporal model using MODAPTS from measurements derived from the spatial model. For the second phase, ergonomic assessments were performed on each job using the developed temporal model.

To initialize the MBWA for any given job, information regarding the workspace is collected from various data sources (such as work standards, work environment, work equipment and objects, process sheets, and any historical data). The first step of performing an ergonomic assessment using MBWA was to create a suitable virtual representation of a workspace. It is important to note that an exact representation of any given workspace is difficult to recreate exactly; a sufficiently accurate representation was sought that could reflect key aspects of the workspace as identified by the given data sources. For the purpose of this analysis, key work locations and key work objects were identified.

1. Create a 3D model of workspace (Autocad 2021) - any CAD packages can be used for this purpose.

2. Determine work movements by identifying key work locations and key work objects from job standards and process sheets. Extrapolate movement distances from the 3D workspace model.

For the first step, CAD models of the workspace for each job analyzed were produced using Autocad 2021 informed by work environment specifications and process sheets. In some instances, specific machinery used in a job was known, which allowed for more accurate spatial recreation (an example is shown in Appendix A Figure A.1). An example of a completed workspace representation using AutoCAD is shown in Figure 2.1.

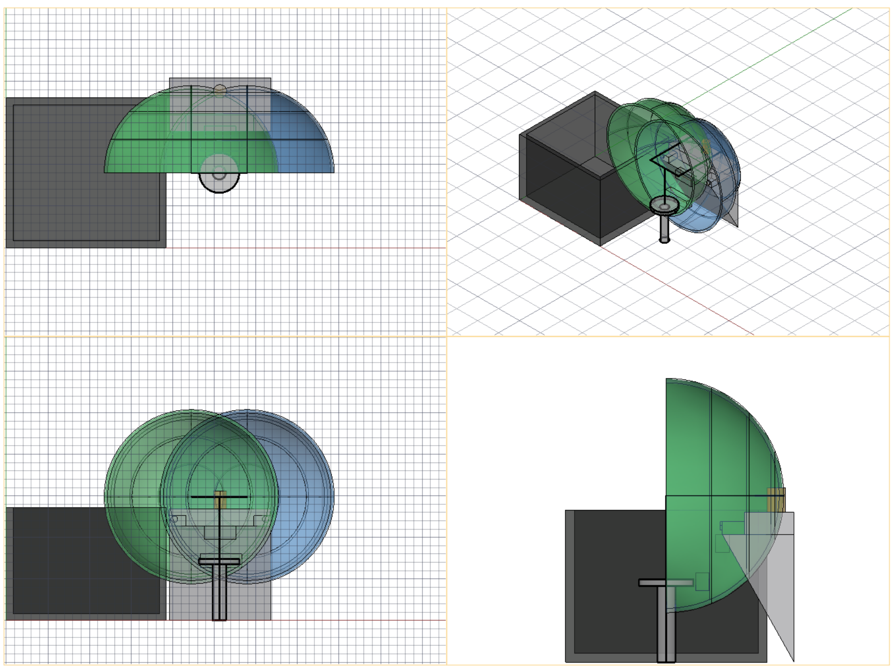


Figure 2.1: AutoCAD model of assembly welding workspace

2.3.3 Application of MODAPTS

Following the development of a Spatial representation of the workspace, movement patterns and MODAPTS were determined next using the following; the steps are shown in the flowchart Figure 2.2 where each step corresponds to the labeled number on the flowchart.

1. Determine work method by identifying key work locations and key work objects from job description from provided workspace information.
2. Create a 3D CAD model of the workspace using existing information and extrapolate hand movement distances between key work locations from the 3D virtual workspace model.
3. Use MODAPTS to determine time required to perform each step using the distances from the 3D workspace model. MODAPTS times are expressed as integer values of Mods (1 Mod = 0.129s). Perform MODAPTS on video recording of a worker performing the job. MODAPTS will be determined from a combination of movement patterns of the workers as well as documented physical measurements.
4. Perform a time study on individual steps and elements of job (Latko et al., 1997)
5. Compare step-by-step differences from Model-Based approach to observational time study as percent differences. It should be noted that the time-study approach will have variability between the different cycles observed, where the Model-Based approach produces the same time prediction for each step.
6. Update decisions rules used for Model-Based PTS as needed.

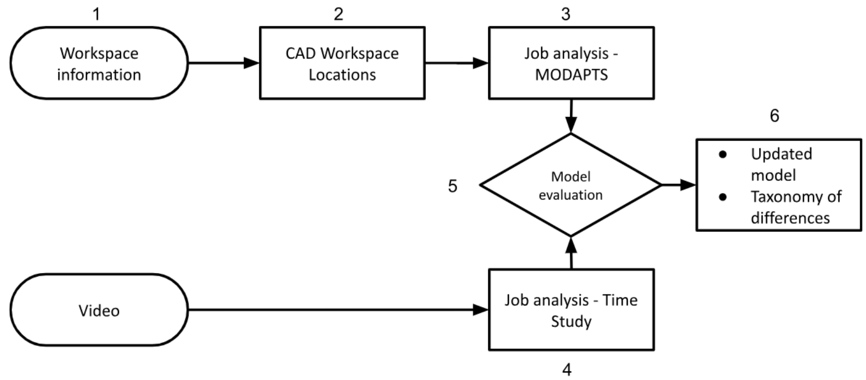


Figure 2.2: Flowchart of developing a full spatial and temporal model. The top shows the process for MBWA, and bottom shows the process for the traditional observation based approach

From the data sources informing about the job, key work objects and locations can be determined. An example of this is shown in Table 2.2. It is important to note that the data sources often list out extra tools, equipment, or locations that are only used in irregular circumstances. The analysis focused on normal work cycles with irregular actions and elements excluded from analysis. Following, the work standards of the task these locations and objects can be mapped onto the spatial representation of which hand the worker is interacting with the objects, shown in Figure 2.3. Further, with work standards and job descriptions, the flow of work materials between different work locations can be mapped out across time demonstrated in Figure 2.3. Together, this creates a spatial-temporal relationship of how the worker interacts with all the tools, materials, and work locations for a work cycle.

Table 2.2: Key work objects for a sample job analyzed (Assembly Welding), with Materials, tools, and locations of the workstation identified. Materials used are designated with "M" – for example Material 1 (M1) is a bracket; Tools designated with a "T", and locations are designated with "L" with subscripts indicating different locations.

Work objects: (Part/tool/control)	**Location**	**Other (Not included in study)**
M1: Bracket	L_A: RH Control Button	T2: Air hose
M2: Bolt	L_B: LH Control Button	T3: Rake
T1: Welding Rig	L_C: Bolt Location	L_G: Hopper (Extra brackets)
T1.1: RH Control	L_D: Bracket Location	
T1.2: LH Control	L_E: Welding Rig	
	L_F: Triwall - assembly deposit location	

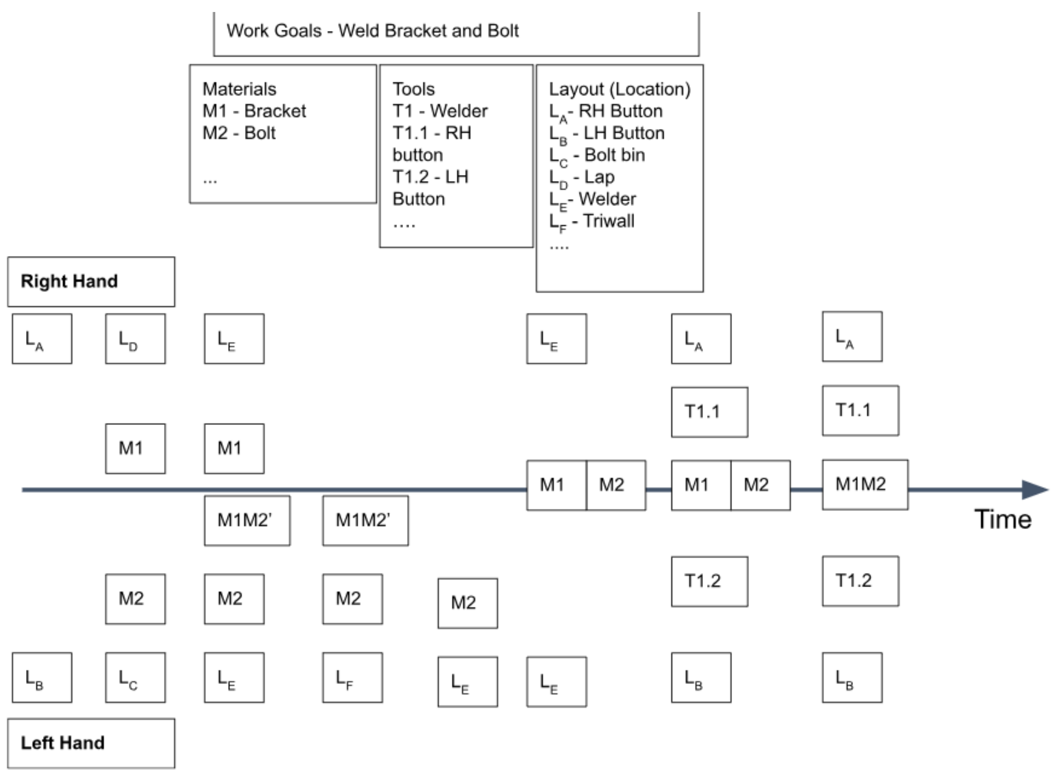


Figure 2.3: Mapping material and hand location based off of task description (Assembly spot welding) across time.

Figure 2.3 maps out the integration of the different parts and locations from Table 2.2 along a temporal time axis. For example, from analyzing the work standards, the RH will first interact with the first material (M1 – Bracket) moving from Location L_A (RH button) to Location L_D (Worker lap), while the LH will interact with the second material (M2 - Bolt) moving from Location L_B (LH Button) to Location L_C (Bolt Bin). The worker will then bring both parts together at Location L_E (Welder). Following this analysis method, a complete timeline of how the worker interacts with the different materials and locations of the workstation can be established. Combining the timeline created and the key locations on the spatial model, movement patterns of each hand can be extrapolated and then used for application of a Predetermined Time System (PTS) (Figure 2.4, 2.5).

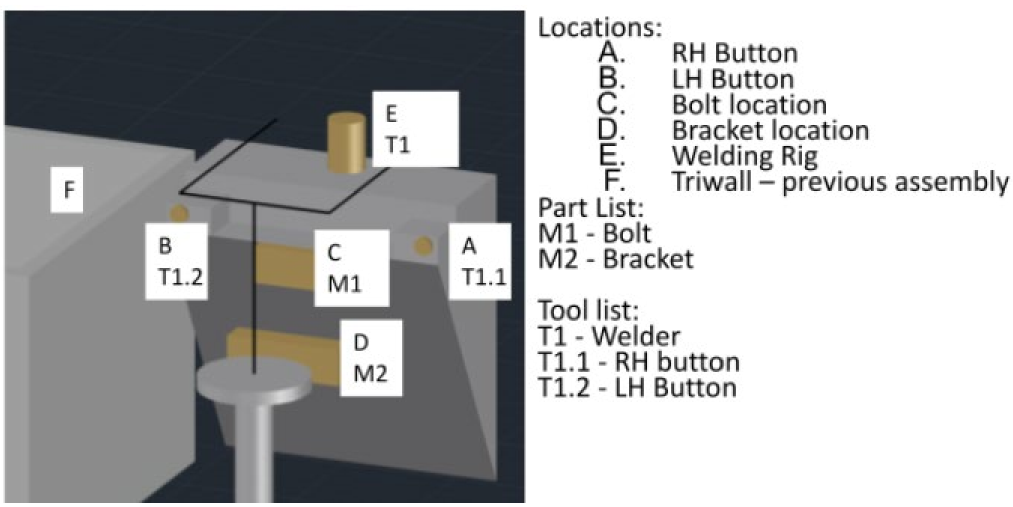
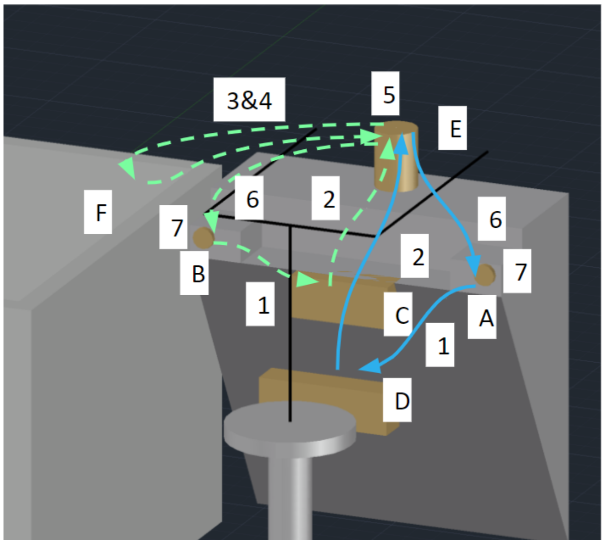


Figure 2.4: Key locations identified on the spatial representation of the workspace along with material and tool locations



1. Move hands from buttons on machine to reach for bracket and bolt
   - Get bracket from lap using right hand
   - Get bolt using left hand
2. Move hands to rig
   - Move bracket to machine rig using right hand
   - Remove previous assembly using left hand while holding bolt
3. Put previous assembly into triwall using left hand
4. Move left hand back to rig
5. Align parts on rig
   - Align bracket on welding machine using right hand
   - Align bolt on welding machine using left hand
6. Move hands to buttons
7. Activate Welder by holding buttons

Figure 2.5: Movement patterns for each hand (Right hand shown by blue solid lines, left by green dotted lines) based off of job description mapped onto critical locations on spatial virtual model of job analyzed

With a sequential order of locations, the movement distances between each step can then be determined and used for MODAPTS analysis following the distances rules given in the MODAPTS handbook (MODAPTS, 2020).

2.4 Results

Autocad was used to generate 3-D workspace models for five different work activities. The CAD spatial models were based on job standards describing the workspace, supplemented with any manufacturer's specifications on tool/machine dimensions. In order to determine critical locations on the spatial model, job standards describing the needed sequence of steps to complete a task were used. From the steps, critical locations that the worker needs to reach and work objects that the worker needs to interact with can be identified. Connecting the dots of each of these work objects and work locations, movement patterns were determined. Using the movement patterns and measurements from the 3-D workspaces, MODAPTS analysis was performed on all five jobs. The comparison between the Model-predicted results and the time study results are shown in Table 2.3.

Table 2.3: Model predicted time and observed cycle times and Duty cycles for five different industry jobs

Job analyzed	Cycle time (s)										Descriptive Stats
	Model predicted	5.93	5.93	5.93	5.93	5.93	5.93	5.93	5.93	5.93	
	Time study	5.87	6.27	6.65	5.8	6.69	6.49	6.98	7.07	5.78	(5.78-7.07; 6.49); 6.4±0.5, SE=7.78%
T-shirt	Percent difference	-1.09	5.36	10.77	-2.31	11.30	8.57	14.99	16.07	-2.66	(-2.66-16.07; 8.57); 6.78±7.32, SE=108.06%
	Model predicted	6.19	6.19	6.19	6.19	6.19	6.19	6.19	6.19	6.19	
	Time study	8.08	7.71	6.59	5.56	6.9	6.07	5.89	5.82	5.55	(5.55-8.08; 6.07); 6.46±0.93, SE=14.39%
Assembly Welding	Percent difference	23.39	19.71	6.07	-11.33	10.29	-1.98	-5.09	-6.36	-11.53	(-11.53-23.39; -1.98); 2.58±12.99, SE=504.57%
	Model predicted	4.77	6.21	6.54	6.54	7.13	6.43	5.85	6.55	6.02	
	Time study	4.37	5.57	6.49	7.70	6.87	4.63	7.78	6.29	4.88	(4.37-7.78; 6.29); 6.06±1.28, SE=21.08%
Case stacking	Percent difference	-9.15	-11.49	-0.77	15.05	-3.73	-38.91	24.79	-4.18	-23.40	(-38.91-24.79; -4.18); -5.76±18.88, SE=-328.1%
	Model predicted	10.04	9.46	4.23	9.12	9.71	9.01	8.43	7.83	5.86	
	Time study	10.63	8.66	3.98	7.59	11.81	11.19	9.58	9.08	6.77	(3.98-11.81; 9.08); 8.81±2.44, SE=27.7%
Pizza stacking	Percent difference	5.55	-9.24	-6.28	-20.20	17.82	19.44	11.99	13.77	13.44	(-20.2-19.44; 11.99); 5.14±13.85, SE=269.3%
	Model predicted	6.76	7.18	4.52	6.76	7.18	4.52	6.76	7.18	4.52	
	Time study	6.21	6.84	3.91	7.53	5.14	5.63	6.37	8.42	5.05	(3.91-8.42; 6.21); 6.12±1.37, SE=22.44%
Chemical bottle Line	Percent difference	-8.86	-4.97	-15.60	10.23	-39.69	19.72	-6.12	14.73	10.50	(-39.69-19.72; -4.97); -2.23±18.49, SE=-828.85%

In addition, the predicted times from the MODAPTS coding from the Model-based approach for each work step was compared to the results from the time study for the T-shirt job in Figure 2.6. There was a total of eight movement steps per cycle with five distinctly different predicted MODAPTS times. Figure 2.6 (top) shows all the steps as a point, while Figure 2.6 (bottom) shows the average for each step with standard deviation. An X=Y line was drawn on these plots – if there was perfect agreement all of the data should fall on this line. From visualizing the data in Figure 2.6, there were a group of work steps that the model-predicted times were far shorter than what was observed via time study. These were highlighted using a grey dotted box.

Lastly, the times from MODAPTS coding predicted from the Model-based approach were separated into movement and terminal elements. The movement Mods and the terminal Mods were then plotted against time study observed times in a scatter plot shown in Figure 2.7 and a bar chart in Figure 2.8. In Figure 2.7, an X=Y line again was drawn, and there were work-steps where the Model-based approach underpredicted; these steps were highlighted using a grey dotted box. In Figure 2.8, key differences between the Model-based approach and time-study approach were highlighted with a grey box.

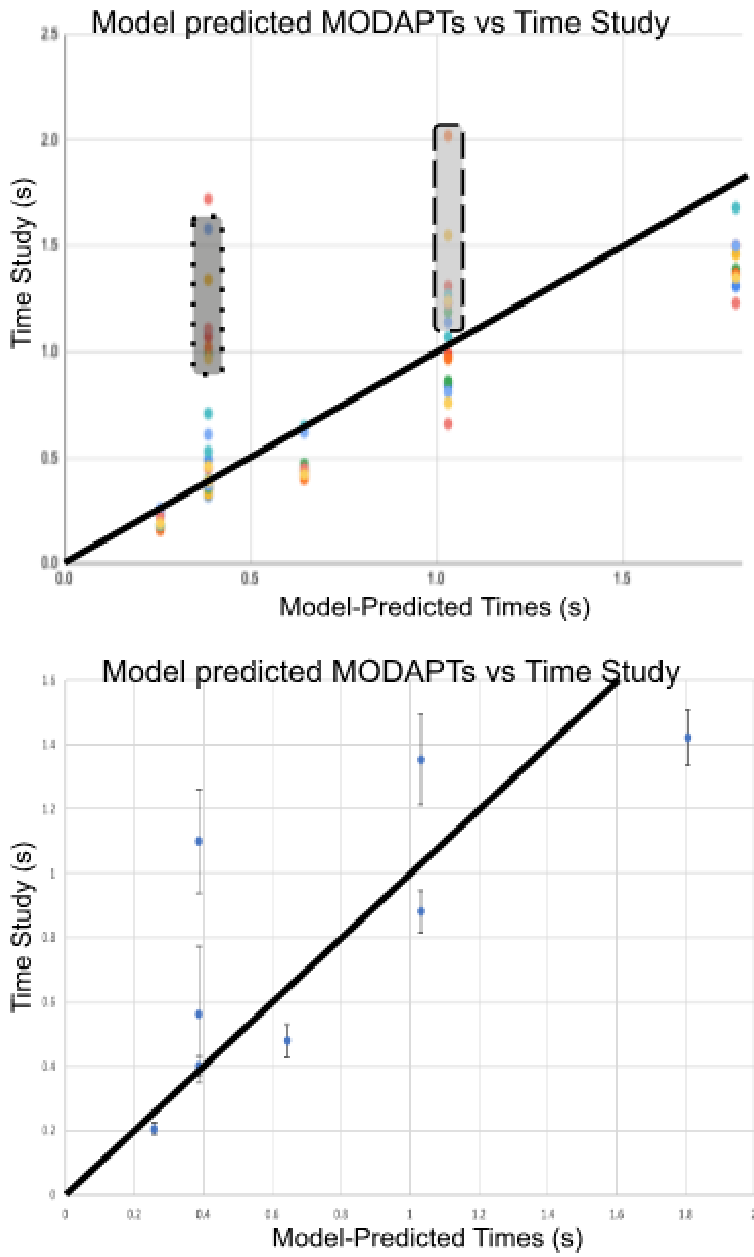


Figure 2.6: (Top) Scatter plot of time study times compared to the Model-Predicted MODAPTS times for T-shirt job (black line: y=x). The grey dotted boxes indicate work steps where there was a large percentage difference between the time-study approach and the Model-predicted approach (Bottom): Average and standard deviation for each step

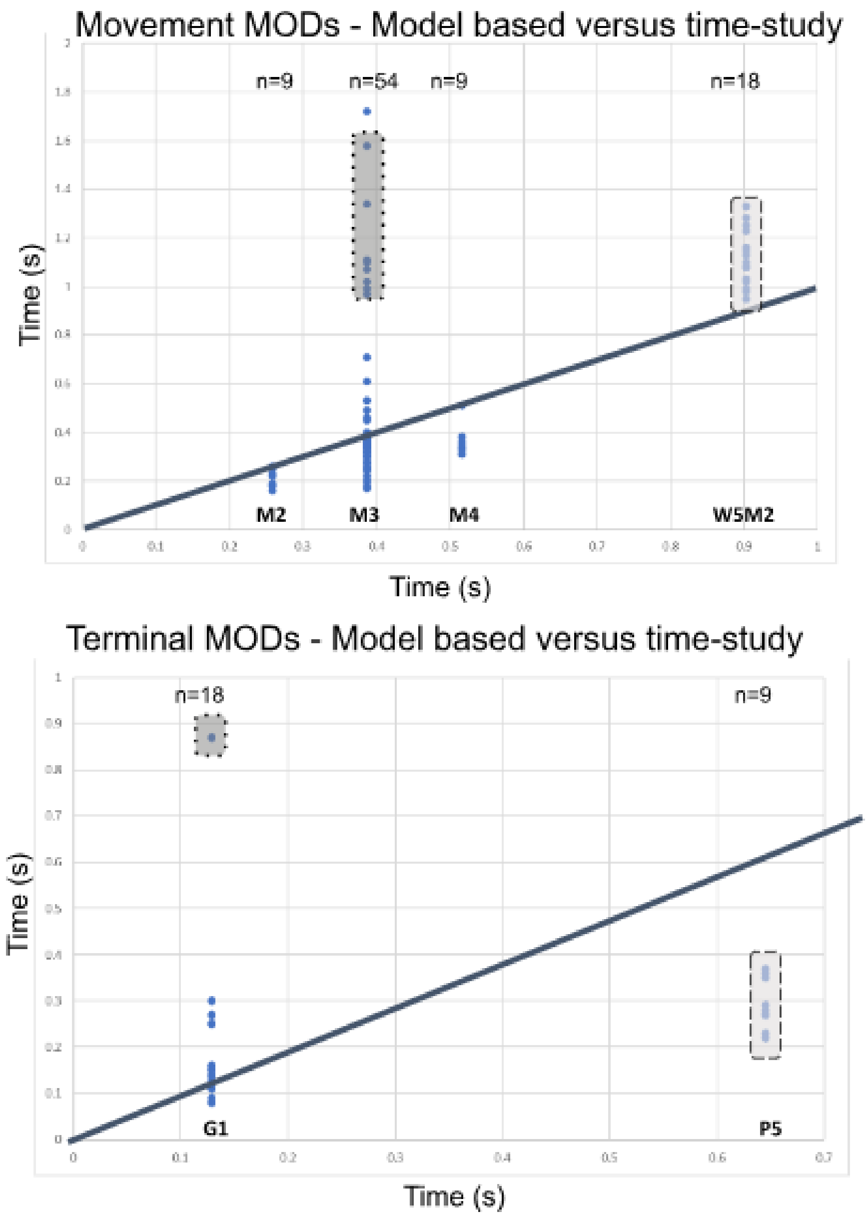


Figure 2.7: (Top): Scatter plot of model-based movement mod predictions vs time-study; (Bottom): Scatter plot of model-based terminal mod predictions vs time-study, The grey dotted boxes indicate work steps where there was a large percentage difference between the time-study approach and the Model-predicted approach

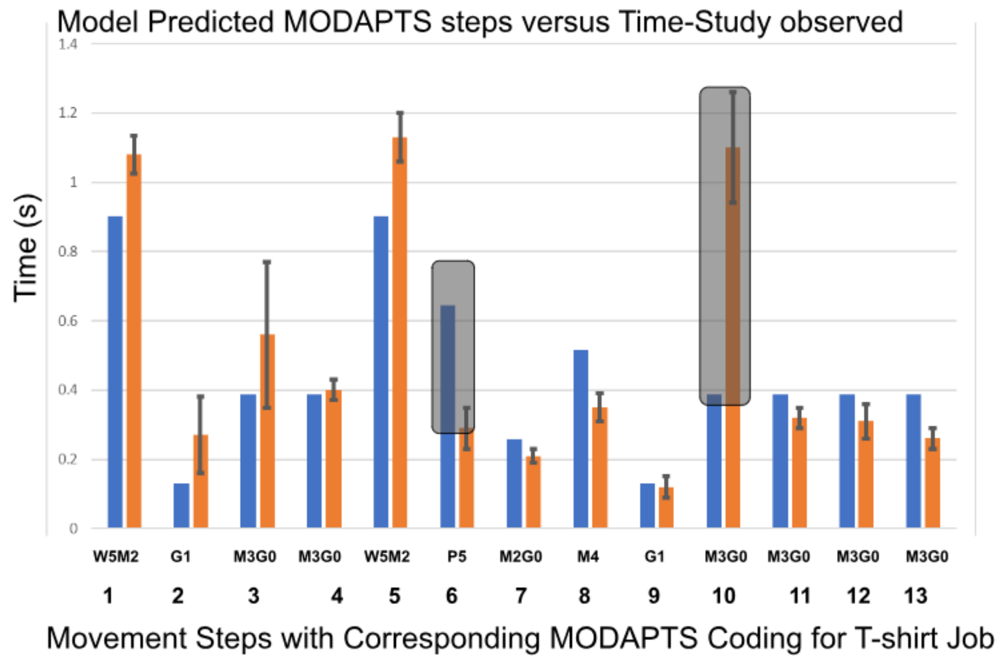


Figure 2.8: Model Predicted MODAPTS times (left bars) versus time-study observations (right bars with standard deviation) for each individual MODAPTS step; The grey dotted boxes indicate work steps where there was a large percentage difference between the time-study approach and the Model-predicted approach

2.5 Discussion

2.5.1 Model Agreement

There is a good level of agreement between the times predicted using the Model-based approach framework and the time study data where none of the jobs observed had an average percent difference of greater than 7% between the predicted and time study results (Table 2.3). One weakness of this analysis is that due to there being no variance from the Model-Based approach, no formal statistics were performed, and model agreement was only measured as a percentage difference. In addition due to this being a new model, there are no standardization on what percentage difference would be considered adequate. It should also be noted that with the exception of the T-shirt job, the standard deviation of percent error for the other jobs are all greater than 12%. This may be due to the fact that the T-shirt job is the only job that was on a machine-paced cycle, with the screen printer rotating at fixed intervals. While the three case stacking jobs all have a steady stream of cases coming from upstream, the workers have more leeway to alter work pace and still keep up. The model predicted results were higher than the time study results for two of the jobs (Chemical bottling line, and Beverage Case stacking). This is likely due to the fact that workers are taking extra affordances (such as not rising all the way after picking something up or twisting at awkward angles) that would not be predicted using MODAPTS. On the other hand, the jobs where the model-based approach underpredicted versus the time studies, the jobs again had extraneous factors that MODAPTS did not capture, namely: for the Assembly Welding job, the worker handled small objects with gloves leading to increased likelihood of fumbling a part; for T-shirt printing job, manipulating flexible material may require higher precision of movements; and for the Pizza stack job, the worker carried two boxes at once, which may require grip altercations.

2.5.2 MODAPTS Taxonomy Update

When looking at the movement steps of different cycles within the T-shirt job, there were two steps where the time study data were significantly higher than the model-based approach results. One of these (dark gray shading with dotted border - Figure 2.6 top) the model-based approach predicted to be a M3G0 based on the short distance that is moved. However, when performing observations, it can be seen that fine adjustments of flexible materials were being performed at this step, something that MODAPTS does not cover. These would be classified as a series of 3xM3P0 which is inherent to the nature of the material, with the flexibility of the material potentially changing tolerances and distances of movement. The second group (light gray shading with dashed border - Figure 2.6 bottom) had smaller, but still regularly higher time study results than the model-based approach results. This group, coded as W5M2G1, represents a larger distance to be covered by a single step; however, due to constrained space, that distance may take longer than the time associated with the assignment of a “W5.” Both of these discrepancies can also be seen in Figure 2.7 top with corresponding highlighted areas. There were also two outliers in Figure 2.7 bottom. The first (highlighted dark gray with dotted borders) was a one-time fumble of material which was an anomaly. The second area (highlighted light gray with dashed border) is of more interest. The model predicted a P5 terminal element due to work standards indicating that the t-shirt must be aligned onto the screen printer but did not specify constraints based on the object and destination involved. After the time-study was performed, it could be seen that the alignment does not happen where the model originally predicted, but at a later step. This can be seen in Figure 2.8. The model overpredicted the amount of time for Step 6 while underpredicted the time for Step 10 - this supports the idea that alignment happens at Step 10 rather than Step 6. From these discrepancies, a list of suggested taxonomy updates was introduced with the hopes of aligning the model-based approach better with what was observed through time studies (Table 2.4).

Following this initial study to develop the methodology of integrating different tools using a model-based approach, there are a few follow up steps needed. First, ergonomic exposure assessments for the five jobs used for this study will be performed. In addition, another follow up would be to add in more job variability to the initial sample from this study. In this study, the jobs used leaned heavily towards manufacturing, so more variety in job types and movement patterns may be needed for a more robust model.

Table 2.4: Taxonomy for decision rules developed from jobs analyzed

Use Case	**Decision Rule**
Measured distance between work locations fall slightly above a MOD defined distances (for example measured distance of 22”)	Round down to lower MOD to allow for body assist
Puts for small parts to non-specific locations	Reduce Movement MOD by 1
Warehouse work - Distances on cusp of M9 (for example of puts)	Add in extra walk element to reduce movement MOD
Warehouse bends and arise	Add in extra walk element to reduce movement MOD
Both hands interacting with same object	Take longer coding for both hands and apply to both hands
When interacting with small part using gloved hand	Increase “Get” Coding by 1 to accommodate for handling difficulties If “Get” is maxed out, add in J2 juggle coding

2.5.3 Key Limitations

There are a few limitations of the work thus far. While this study has demonstrated the feasibility of using work standards as an input to create spatial and temporal modeling of the relationship between the worker and the work, there still needs to be an understanding of the biomechanics and loads experienced by the worker. Ergonomic exposure assessments for the five jobs used for this study need to be performed. Next, this study has identified that when using MODAPTS for temporal modeling, there are use cases where the predictions are not particularly accurate; in order to build up a more complete taxonomy of updates for temporal modeling, a wider variety of jobs involving different movement patterns should be analyzed in the future. In this study, the jobs used leaned heavily towards manufacturing, so more variety in job types and movement patterns may be needed for a more robust model.

2.6 Conclusion

The key objectives of this chapter were to formalize the application of the MBWA framework in a variety of different work tasks. Different workers and work interactions were determined from the underlying work standards so that movement patterns and the timing of it are all grounded from the fundamental nature of the job task. Spatial and temporal modeling was performed using AutoCAD and MODAPTS respectively. Overall, using the model-based approach in assessing worker movement patterns was a success. There was a good level of agreement between the model-predicted cycle times and traditional observer-based time-study times. Out of the jobs analyzed, none of the differences between model and observation methods were greater than a 7% difference. While the model performance lags when looking at specific movements and use-cases, taxonomy updates were suggested. In addition, it should be noted that MODAPTS was used in this study due to the high relevance to industry; however, different tools can also be used for temporal modeling. In addition to demonstrating the functionality of a Model-based approach, this study has also shown the ability for contextual analysis of different work tasks. This allows for prediction and interpretation of potential work-related issues prior to putting a worker into the system.

References

Armstrong, T. J., Keyserling, W. M., Grieshaber, D. C., Ebersole, M., & Lo, E. (2003). Time based job analysis for control of work-related musculoskeletal disorders. In 15th Triennial Congress of the International Ergonomics Association, Seoul, Korea.

Armstrong, T. (2023). Strength Demand and Capacity, T. Armstrong. https://websites.umich.edu/~tja/fatigue/fatigueLocalized.html.

Armstrong, T. J. (2021). CAD and MODAPTS Models for Assessing Localized Fatigue. In Congress of the International Ergonomics Association (pp. 682-687). Springer, Cham.

Autocad (2021) 3D Design Software, Autodesk

Barr, A. E., Barbe, M. F., & Clark, B. D. (2004). Work-related musculoskeletal disorders of the hand and wrist: epidemiology, pathophysiology, and sensorimotor changes. Journal of orthopedic & sports physical therapy, 34(10), 610-627.

Bernard, B. P., & Putz-Anderson, V. (1997). Musculoskeletal disorders and workplace factors; a critical review of epidemiologic evidence for work-related musculoskeletal disorders of the neck, upper extremity, and low back.

Cho, H., Lee, S., & Park, J. (2014). Time estimation method for manual assembly using MODAPTS technique in the product design stage. International Journal of Production Research, 52(12), 3595-3613.

Freivalds, A., & Goldberg, J. H. (1988, October). Instructional Use of Personal Computers in Human Factors Labs. In Proceedings of the Human Factors Society Annual Meeting (Vol. 32, No. 7, pp. 468-472). Sage CA: Los Angeles, CA: SAGE Publications.

Freivalds, A., & Niebel, B. (2013). Niebel's Methods, Standards, & Work Design. McGraw-Hill higher education.

Gilbreth, F. B., & Kent, R. T. (1911). Motion study: A method for increasing the efficiency of the workman. D. Van Nostrand Company.

Heyde, G. C. (1983). MODAPTS plus. Heyde Dynamics Pty. by arrangement with the Australian Association for Predetermined Time Standards & Research.

Jones, T., & Kumar, S. (2010). Comparison of ergonomic risk assessment output in four sawmill jobs. International Journal of Occupational safety and ergonomics, 16(1), 105-111.

Kong, Y. K., Lee, S. Y., Lee, K. S., & Kim, D. M. (2018). Comparisons of ergonomic evaluation tools (ALLA, RULA, REBA and OWAS) for farm work. International journal of occupational safety and ergonomics, 24(2), 218-223.

Latko, W. A., Armstrong, T. J., Foulke, J. A., Herrin, G. D., Rabourn, R. A., & Ulin, S. S. (1997). Development and evaluation of an observational method for assessing repetition in hand tasks. American Industrial Hygiene Association Journal, 58(4), 278-285.

Mallembakam, V. R. (2020). Incorporating Modular Arrangement of Predetermined Time Standard with a Wearable Sensing Glove (Doctoral dissertation, University of Windsor (Canada)).

Mathiassen, S. E., & Winkel, J. (1996). Physiological comparison of three interventions in light assembly work: reduced work pace, increased break allowance and shortened working days. International archives of occupational and environmental health, 68(2), 94-108.

Mathiassen, S. E., & Winkel, J. (1991). Quantifying variation in physical load using exposure-vs-time data. Ergonomics, 34(12), 1455-1468.

MODAPTS (2020). International MODAPTS Association, 5119 Kara Dr., Jonesboro, AR 72401, US. https://modapts.org/

Rabourn, R. A., Ulin, S. S., and Armstrong, T. J. (1996). Initiating Ergonomics Activities In Small Companies. In A. Mital, H. Krueger, S. Kumar, M. Menozzi and J. E. Fernandez (Eds.) Advances in Occupational Ergonomics and Safety I, (pp. 925-930).

Rempel, D. (2018). 1631c Recent changes to the ACGIH hand activity level TLV.

Smith, A. (1863). An Inquiry into the nature and causes of the Wealth of Nations... New edition, revised, corrected and improved.

Takala, E. P., Pehkonen, I., Forsman, M., Hansson, G. Å., Mathiassen, S. E., Neumann, W. P., ... & Winkel, J. (2010). Systematic evaluation of observational methods assessing biomechanical exposures at work. Scandinavian journal of work, environment & health, 3-24.

Taylor, F. W. (2004). Scientific management. Routledge.

Ulin, S. S., Armstrong, T. J., Snook, S. H., & Monroe-Keyserling, W. (1993). Examination of the effect of tool mass and work postures on perceived exertion for a screw driving task. International Journal of Industrial Ergonomics, 12(1-2), 105-115.

Ulin, S. S., Rabourn, R. A., Armstrong, T. J., and Lau, M. H. (2006). Ergonomics Support for Small Companies. Proceedings of the International Ergonomics Association 16th World Congress on Ergonomics, Maastricht, Netherlands.

Wells, Richard, Svend Erik Mathiassen, Lars Medbo, and Jørgen Winkel. "Time—a key issue for musculoskeletal health and manufacturing." Applied ergonomics 38, no. 6 (2007): 733-744.

Wu, S., Wang, Y., BolaBola, J. Z., Qin, H., Ding, W., Wen, W., & Niu, J. (2016). Incorporating motion analysis technology into modular arrangement of predetermined time standard (MODAPTS). International Journal of Industrial Ergonomics, 53, 291-298.

YASUKOUCHI, A., ARAI, K., OHASHI, J., SAKO, H., & KAT, K. (1993). Effects of the Directlon and Distance of Horizontal Arm Movements on Local Muscular Strain: A Fundamental Study on the Teller Workplace in Bank. The Annals of physiological anthropology, 12(6), 341-350.

CHAPTER 3

Integrating Exposure Measures into the Model-Based Work Assessment Framework

Abstract

Prior work has demonstrated the application of combining spatial and temporal modeling to proactively predict movement patterns and movement behaviors of a worker with a known work standard. This approach, combining CAD modeling and PTS modeling, was able to predict work cycle time accurately without needing observers or traditional time-study methodologies. This work aims to expand on the prior work, by modeling physical exposure metrics experienced by the different workers throughout the work cycle. The movement patterns from the previous study were broken down based on if the worker was performing an active exertion or being idle. Using ACGIH TLV, duty cycle was computed using a model-based approach, as well as a traditional observation-based approach. Overall, the model-based approach underestimated the duty cycle for each task by 9-21%. From those results, additional taxonomy changes were suggested for where the model does not accurately predict worker exertion.

3.1 Introduction

The main objective of this study was to demonstrate the flexibility of the model; both to predict the exposure metrics experienced by workers, and to easily do post analysis altering the workflow to reduce exposures with just the work standards.

With fatigue being a precursor to long term WMSDs, it is important to understand fatigue risks for workers and different work tasks. To quantify this, there exist many fatigue-risk assessment methods that are commonly used, with these methods typically fall under three bins - Self-Report, Observer based, and physiologic-response based. Self-reporting methods include tools like the Quebec Exposure Checklist, the Nordic Musculoskeletal Questionnaire (NMQ) and the NASA TLX (Crawford, 2007; David et al., 2008; Hart, 2006). While these may allow for the capture of a snapshot of what the worker is experiencing, they do not address the underlying causes of discomfort or fatigue due to not establishing detailed relationship of the spatial-temporal worker work interaction. In addition, the QEC checklist still utilizes an external expert observer, and introduces other drawbacks related to observation-based tools. Biomechanical loads can change and be altered based on differing workplace setups, the tools used, work habits, as well as the workers themselves. Thus, results can vary a lot from observer to observer, from worker to worker. Observation based analysis is also labor intensive, and depending on when the observation happens, factors such as work process, equipment, materials, conditions, and worker could change. For a good understanding, multiple workers over time and space would need to be observed. However, with a model based approach normal expectations of worker-work relations and exertions can be predicted.

A formalized framework - the Model-Based Work Assessment Framework (MBWA) – can be applied for proactive job analysis and for establishing normal performance was proposed and examined in Chapter two of this dissertation. Chapter two demonstrated the ability to use the MBWA framework to build up a model of the worker-work interactions through work standards and work goals, providing contextualization for further work assessment. This chapter aims to close the loop after spatial and temporal models have been created and to generate usable metrics about worker exposure. Study two applies ergonomic exposure assessments to the five jobs analyzed in Study one and demonstrates the uses of combining CAD models, PTS and exposure measures to determine hand load patterns by applying the ACGIH TLV for hand fatigue (Rempel, 2018; Bonfiglioli et al., 2013). This chapter then aims to close the loop and demonstrate how these models can also anticipate the effect of variations in work layout or work standards on the ACGIH TLV. The framework will allow for identification of key work aspects and a method to characterize different sources of variance and anticipate when variability might occur. Specifically, by applying this framework, jobs and job standards can be optimized prior to inserting a worker into the system. This would be a prospective approach whereas existing methods are often retrospective studies. An Exposure index for the hand was calculated using both the Model-based approach as well as the traditional time study approach. A workflow alteration analysis was also performed to demonstrate theoretical interventions impacts on exposure.

3.2 Methods

Load patterns were derived from a combination of the movement patterns and MODAPTS predicted times. The following sections will describe the process used to analyze the jobs and show in depth one specific job analyzed (namely assembly spot welding) which includes engineering improvements suggested from the MBWA and resulting load pattern changes.

3.2.1 Ergonomic Assessment

Following the generation of a spatial and temporal model of a given job, the following steps were used to determine ergonomic and fatigue for upper limbs (detailed flowchart shown in Figure 3.1).

1. Using the Model-based framework predicted steps and elements, determine the materials and tools that a worker is interacting with for each work step and work element from the work standards.
2. Forces as %MVC were estimated for each work step and work as described by Ebersole et al. (2005). Without observation of the specific workers, strength capabilities can be estimated based on existing studies. For unknown workers, the strength capabilities were set to 50% percentile male or female.
3. The duty cycle, DC, was computed as the sum of times in which the force was greater than 7% MVC for each hand divided by the total work cycle time and any process time.
4. The resulting DC was then compared with the ACGIH TLV® for hand/forearm fatigue.
5. The above metrics were also computed using time-study work steps and work elements generated from video observations.

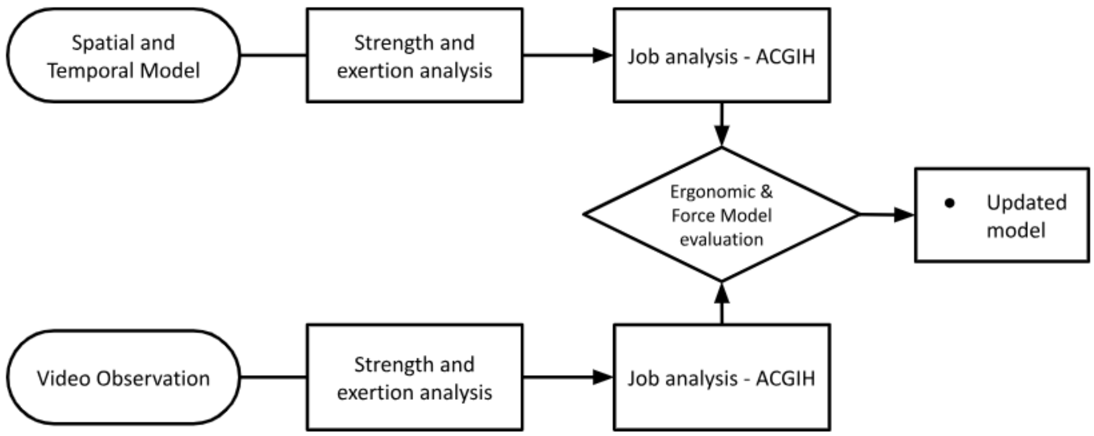


Figure 3.1: Flowchart of developing an Ergonomic and Force model. The top shows the process for MBWA and bottom shows the process for the traditional observation based approach

3.2.2 Suggested work pattern change

With an ergonomic profile of each job generated, motion patterns that cause potential load pattern concerns were identified. Initial exploratory work was done on the Assembly Welding job to identify altercations that could be made to the workflow in order to reduce the duty cycle on the hand.

1. Identify movement steps that require unnecessary hand exertions
2. Alter movement steps so that hands can remain idle for longer
3. Compare ergonomic metrics before and after work altercation.

3.3 Results

Spatial and temporal modeling was performed on the same five jobs as used in Chapter two. After generating a model to determine movement pattern through space and movement times, strength requirements and expenditures can be calculated. For each job, worker strength capabilities were estimated depending on the type of grip used

(Armstrong, 2023). Following, the load was estimated using existing work standards or from part description (i.e. shape, size, and density of material). The duty cycle (DC) was calculated as a percent of time exerting force greater than 7% MVC out of the total task cycle. A summary table comparing the MODAPTS time and duty cycle results from both the Model-based approach and the traditional timeline observation approach is shown in Table 3.1.

Table 3.1: Model predicted time and observed cycle times and Duty cycles for five different industry jobs

	Duty Cycle		
Job analyzed	Model Predicted (%)	Time study (%)	Percent difference
T-shirt	11	12.2	1.5
Assembly Welding	RH - 65 LH - 31	RH - 83 LH - 31	RH - 21.69 LH - 0
Case stacking	58	69	15.94
Pizza stacking	60	66	9.09
Chemical bottle Line	59	65	9.23

3.3.1 Work alteration Duty Cycle reduction

After generating force estimates for the Assembly Welding job, exploratory work was done on suggesting workflow changes in order to reduce the amount of sustained force exerted by the right hand during the middle part of the job cycle (highlighted in yellow in Figure 3.2). The time weighted exertions for the right hand in this task was a total of

11% MVC. At this exertion level, the maximum recommended duty cycle is 73%; the predicted duty cycle for this job was 65%. While the predicted value does not exceed the maximum recommended, individual variances between workers could easily cause the duty cycle to increase above the maximum recommended limit (and this was what happened with the observed worker). Analysis of the workflow using identified a period of time where the right hand performed unnecessary exertions; reducing this would reduce the duty cycle significantly. Detailed MODAPTS workflow change is shown in Appendix B Figures B.1 (old workflow) and B.2 (new suggested workflow).

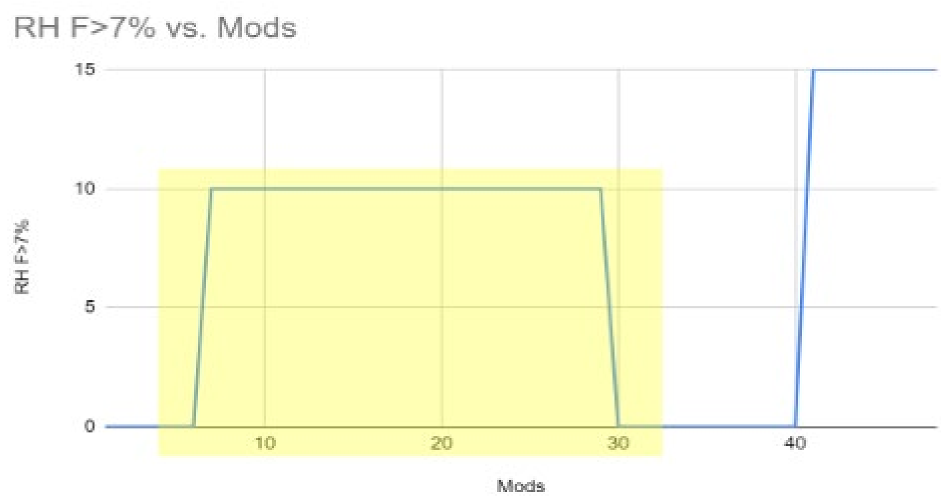


Figure 3.2: Sustained force for over 20 Mods by the Right hand.

By altering the workflow and having the right hand in this case pick up the part at a later time in the work cycle, the duration of sustained force is greatly reduced as shown in Figure 3.3. This reduction in sustained force also resulted in a much lower duty cycle - going from a 65% duty cycle to 42%.

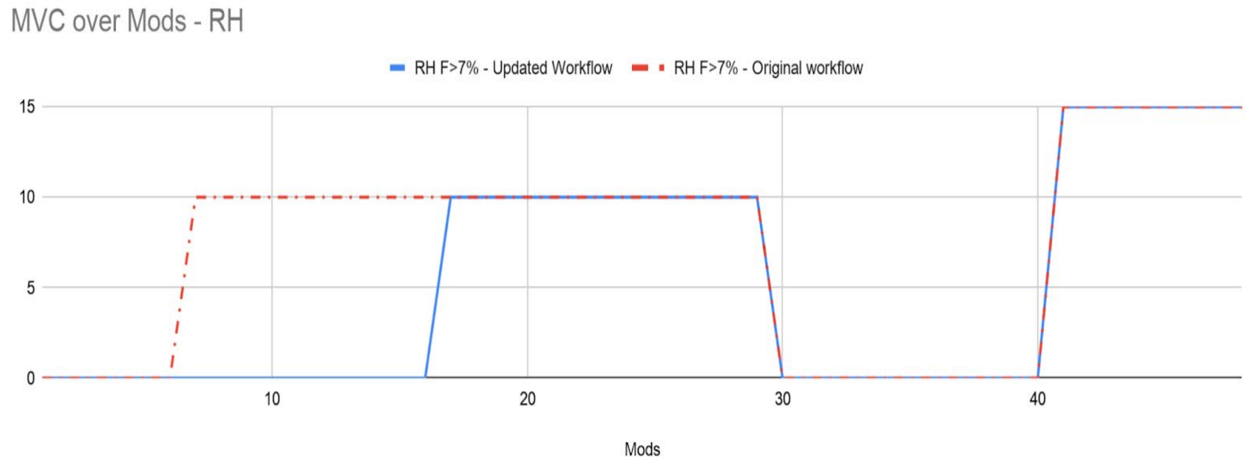


Figure 3.3: Sustained force reduced from over 20 Mods to just over 10 Mods for the right hand

For each job, worker strength capabilities were estimated depending on the type of grip used (Armstrong, 2023). Following, the load pattern was estimated using existing work standards or from part description (i.e., shape, size, and density of material) when possible. When load patterns above minimum threshold was not easily estimated, a minimum value of 7% MVC was assigned. The duty cycle (DC) was calculated as a percent of time exerting force greater than 7% MVC out of the total task cycle. After generating force estimates for the Assembly Welding job, exploratory work was done on suggesting workflow changes in order to reduce the amount of sustained force exerted by the right hand during the middle part of the job cycle (highlighted in yellow in Figure 7). Detailed MODAPTS workflow change is shown in Appendix B Figures B.1 (old workflow) and B.2 (new suggested workflow). By altering the workflow and having the right hand in this case pick up the part at a later time in the work cycle, the duration of sustained force is greatly reduced as shown in Figure 3.3. This reduction in sustained force also resulted in a much lower duty cycle - going from a 65% duty cycle to 42%.

3.4 Discussion

3.4.1 Model Agreement

For the duty cycles between the Model-based approach and the time-study approach, the agreements are also fairly close. The Model-based approach routinely underestimated the duty cycle of each job. This is potentially due to MODAPTS estimation of walking and large movement distances being the same with and without loads. In actuality, for the same distance, the workers would move slower while carrying a load; however, under current MODAPTS rules, unless the load carried is excessively large, no additional time offset is added. This would artificially deflate the amount of time the Model-based method predicts the worker to be interacting with a load.

3.4.2 MBWA Driven workflow updates

Through the use of MBWA, workflow changes were successfully suggested to one of the jobs studied; the initial duty cycle for the job for the right hand was reduced from 65% down to 42%. Although a small sample size, it serves as a proof of concept in which measurable ergonomic improvements in sustained force and duty cycle can be seen. This serves as a reminder to how useful proactive assessment of a workspace and work task can be.

When comparing the duty cycles based on the Model-based approach versus those based on the time-study approach, the agreements are also fairly close (range from 9 - 20% difference). The Model-based approach routinely underestimated the duty cycle of each job, all the differences are under-predictions. This is potentially due to MODAPTS estimation of walking and large movement distances being the same with and without loads. In actuality, for the same distance, the workers would move slower while carrying a load; however, under current MODAPTS rules, unless the load carried is excessively large (over 57lb), no additional time offset is added. This would artificially deflate the amount of time the Model-based method predicts the worker to be interacting with a load. It should also be noted that because the Duty Cycle calculation is done directly using the MODAPTS results from the previous sections, any disagreement between the model-based method and the observation-based method would carry over. Additional taxonomy updates are shown in Table 3.2.

In addition, through the use of MBWA, workflow changes were successfully suggested to one of the jobs studied. Although a small sample size, it serves as a proof of concept in which measurable ergonomic improvements in sustained force and duty cycle can be seen. This serves as a reminder to how useful proactive assessment of a workspace and work task can be. The logical next steps following this will be to perform a follow up study applying the framework in a real-world setting.

Table 3.2: Taxonomy updates from ergonomic assessment

Use Case	**Decision Rule**	**Rationale**
Carrying loads that are under MODAPTS rules threshold for “L” designation	For long walk distances over W5, add in extra L2 load factor	Accounts for slower walking when manipulating potentially awkward loads
Raising loads to or above head level	Consider adding in extra L2 or X4 to accommodate for extra exertion	Accounts for extra time for exertions needed to move loads
Any active exertion involving small parts	Assign 7%MVC	Any noticeable exertion would require muscle activation and be awarded a minimum amount of %MVC
Any material deformation of soft or malleable material that does not reach force threshold of L2	Assign 7%MVC	Any noticeable exertion would require muscle activation and be awarded a minimum amount of %MVC

3.4.3 Key Limitations

There are a few limitations associated with this work as is. First, the only exposure metric that is currently being examined is ACGIH TLV for upper limb duty cycle. Follow up work should examine looking at other input metrics for exposure; the model-based approach is only as good as the tool used to build up the framework. The second limitation comes with the smaller sample size used; while many cycles were examined for each job, there was not a huge amount of variety in the type of tasks performed. In addition, the force measures were estimated and subjective based on the work standards – detailed weights and required forces were not readily available. For more accurate analysis in the future, lab studies should be performed to measure exact forces. Lastly, in future work, different activities involving more varied motion patterns should also be examined.

3.5 Conclusion

Chapter two established the feasibility of using the MBWA framework in analyzing work tasks and worker movement patterns. The key objective of this chapter was to apply the movement pattern data resulting from the MBWA framework approach to assess exposure and dose information for workers. The specific exposure metric used in this study was ACGIH TLV for the upper extremities. The analysis works particularly well when an individual is working with lower weights and lower exertion levels. However, when applied to tasks where larger forces are required, the model often under-predicts the duty cycle. This is likely due to manipulating work objects and tools of larger weights requires extra movement patterns that are not predicted by MODAPTS.

There were a few key findings associated with this Chapter. Following up on establishing the timing of the workers' movement patterns, the exposure risk for each worker was also successfully predicted using the MBWA approach. In addition this methodology demonstrates the strength of the ability to perform proactive analysis. By building up the model from work standards and work goals, it is possible to predict and interpret the fatigue risks as a function of the work without having to put the worker into the system. This allows for predictive modeling of the impacts of changing workflow, workspace layout, and work tools on the worker. This framework can also be used for retrospective work and to iterate potential engineering interventions and workspace changes virtually without the cost of physically changing a workspace.

References

Armstrong, T. (2023). Strength Demand and Capacity, T. Armstrong. https://websites.umich.edu/~tja/fatigue/fatigueLocalized.html.

Bonfiglioli, R., Mattioli, S., Armstrong, T. J., Graziosi, F., Marinelli, F., Farioli, A., & Violante, F. S. (2013). Validation of the ACGIH TLV for hand activity level in the OCTOPUS cohort: a two-year longitudinal study of carpal tunnel syndrome. Scandinavian journal of work, environment & health, 155-163.

Crawford, J. O. (2007). The Nordic musculoskeletal questionnaire. Occupational medicine, 57(4), 300-301.

David, G., Woods, V., Li, G., & Buckle, P. (2008). The development of the Quick Exposure Check (QEC) for assessing exposure to risk factors for work-related musculoskeletal disorders. Applied ergonomics, 39(1), 57-69.

Ebersole, M. L., & Armstrong, T. J. (2006). Analysis of an observational rating scale for repetition, posture, and force in selected manufacturing settings. Human factors, 48(3), 487-498.

Hart, S. G. (2006, October). NASA-task load index (NASA-TLX); 20 years later. In Proceedings of the human factors and ergonomics society annual meeting (Vol. 50, No. 9, pp. 904-908). Sage CA: Los Angeles, CA: Sage publications.

Rempel, D. (2018). 1631c Recent changes to the ACGIH hand activity level TLV.

CHAPTER 4

Development and Evaluation of a Remote Ergonomic Self-Assessment Tool for Work from Home Employees

Abstract

The main objective of this study was to develop and evaluate a Remote Ergonomic Self-assessment Tool (REST) for Work From Home (WFH) workers using a mixed-methods approach. Since the COVID-19 pandemic, many different jobs have been adopted to allow employees to work in a remote or hybrid setting. As a response to the shifting nature of work, there have been many initiatives to understand the health of these Work From Home (WFH) employees. There currently do not exist any simple self-assessment tools to evaluate WFH workers' physical health. As a response, a Remote Ergonomic Self-Assessment Tool was developed using the Model-based Work Assessment Framework. After the development of the Remote Ergonomic Self-Assessment Tool (REST), evaluation was conducted using a mixed-methods approach. The tool was created on Qualtrics and distributed to individuals (n=38) recruited from an online database maintained by a Midwest University in the Midwest. Following, a focus group interview was conducted recruiting individuals (n=6) that had previously completed the REST. In terms of the overall Combined Score of the tool, there were moderate levels of correlation ($r = 0.62$) at high significance ($p < 0.001$) for pace, and a high level of correlation ($r = 0.80$) at high significance ($p < 0.001$) for tool exertion. From the focus

group, the key themes discovered were the importance of: being able to change up the work location and environment, the flexibility of taking breaks, and the ability to procure specialized physical ergonomics tools. We identified the factors of Pace and Tool Exertion as important factors that contribute to the overall combined score. However, from the focus group, the themes suggested that breaks & work flexibility were also important to the workers' overall wellbeing. This informs that the new iterations of this tool needs to include additional questions addressing the type of breaks and what individuals are doing during these breaks. The first iteration of the tool was able to capture important factors of Pace and Tool Exertion, as well as identified some key themes using a focus group. With the findings from our pilot survey results, as well as the focus group interviews, further refinement can result in a simple self-assessment tool for WFH workers.

4.1 Introduction

The objective of this study is to apply the MBWA framework and rigorously design a self-assessment tool by collecting spatial, temporal, and exertion data for Work from Home (WFH) workers. The result of this research is to produce a simple self-assessment tool to self-evaluate for ergonomic risk. As previously mentioned in this thesis, there are inherent drawbacks of self-assessment tools such as self-bias, and only capturing a small snapshot of the worker-work interaction; this study aims to address those drawbacks by systematically understanding the spatial and temporal interactions of the WFH workers and their various workspaces, as well as potential exertions needed for their entire work day. Toward this end we use a mixed-method approach combining survey and focus group data that informs the appropriate and optimal content for such a self-assessment and identifies key areas for future iteration. This addresses a key need as not all WFH workers have access to support for home office ergonomics. Having a self-assessment tool also can act as an estimation for the “cost of entry” for the average worker to be able to safely do remote hybrid work without increased risk of long term Work-Related Musculoskeletal Disorder (WMSD) risks.

4.1.1 WFH & wellbeing

While the COVID-19 pandemic impacted virtually all aspects of daily life, one of the more enduring changes was the adaptation to WFH. It was initially thought that WFH work would be a temporary solution, with workers returning to an office environment once the pandemic was over. However, it is estimated that over half of the U.S. workforce is currently working remotely at least once a week (Parker, Horowitz, & Minkin, 2022). This transition prompted a rapid adoption of new work modalities leading to changes in how individuals interact with their work environments, colleagues, and blending of work, social and home lives. The shifting of work modalities has led to a wave of research focusing on worker productivity and worker wellbeing. National surveys have suggested that working remotely or in a hybrid setting can have benefits for work-life balance, worker well-being, as well as productivity (Parker, Horowitz, & Minkin, 2020; Parker, Horowitz, & Minkin, 2022). However, on the other hand, other studies have suggested that WFH work can also cause struggles with weight-gain, physical pain, technology fatigue, and increased sense of social isolation (Bailenson 2021; Streeter, Roche, & Friedlander, 2021).

One of the primary benefits that has come out of WFH is the increase in flexibility and autonomy - of those who work remotely, 64% indicated that they find it “Easier to balance work/personal life," and 44% reported that they found it "Easier to get work done/meet deadlines," (Parker et al., 2022). Various surveys do touch upon physical wellbeing for remote workers, these questions are broader commentary under the greater umbrella of worker well-being, work-life balance, and productivity. It has been found that blurring the lines between home life and remote work has increased distractions, caregiving demands, thrown off work-life balance, and generally increased stress (Parker et al., 2022; Galanti et al., 2021; Prasad, Vaidya, & Mangipudi, 2020). In addition, those workers who do not have a dedicated home office are more likely to report distractions, increased stress, and decreased overall wellbeing (Bergefurt et al., 2022). Lastly, being more connected to work can cause workers to take fewer breaks which leads to physical discomforts such as headaches (Cropley, Weidenstedt, Leick, & Sutterlin, 2022). While overall wellbeing has been studied in numerous studies, ergonomics within a WFH work have not been specifically focused on. Some employers that switched over to a WFH work modality were able to provide tailored ergonomic assessments of home office spaces, as well as provide the monetary cost of upgrading home office equipment (Chang, 2021). However, these resources are not often available to everyone. The survey tool developed will not focus on existing metrics of psychosocial well-being and productivity but focus solely on the ergonomics of WFH work.

Performing ergonomic assessments for WFH work provides a few unique challenges. It should be noted that many different types of work fall outside of the traditional "office" environment such as gig work or contract work (i.e., Uber or Lyft driving). However, we will be focusing on the WFH aspect of traditional office work but offset it to a home office or other work environment. One assumption is that due to the nature of

WFH work, workers will be completing an ergonomic assessment autonomously. While there have been a few different self-reporting ergonomic tools, none are widely adopted (David, 2005). Existing ergonomic tools generally rely on experts and use observation-based methods for assessing fatigue on Work-Related Musculoskeletal Disorder (WMSD) risks based on posture and force patterns (Kong et al., 2018; Jones, 2010). Unless the employer performs a direct observation-based tailored assessment many WFH workers do not have the expertise nor resources to self-assess. In addition, these assessment tools being dependent on spatial-temporal patterns of work, slight variations to the work setup can have significant impact. Even in highly structured manufacturing jobs there can be minor variations in tools, materials, work arrangement and work methods that can affect ergonomic loads (Armstrong et al., 1986; Ulin et al., 1993). In less structured jobs, such as those performed remotely from home, these variations can become much greater. Commonly, WFH workers will often not have a well-defined workspace or workstation throughout their work day; workers have greater flexibility to blend in their daily home-life with work. In addition, individuals will have specified needs based on their own preferences. Lastly, without follow up observations, it will be difficult to have a holistic understanding of the long-term impacts of sustained remote work on a workers' potential ergonomic risks. With no observer taking meticulous notes of the spatial-temporal patterns of daily work, a self-reporting tool needs to be user friendly and intuitive, while also providing the necessary information for effective assessment.

4.1.2 Model Development

With many potential variations impacting WFH work it is key to establish the different exposures and dosage experienced by the workers. Extended exposures without proper physiological recovery time can lead to long term muscle, tendon, and nerve disorders (Armstrong et al., 1993). A systematic analysis of relevant factors following the Model-based Work Assessment framework (MBWA Framework) was taken as a way to establish spatial-temporal work patterns for a full understanding of exposure metrics (Armstrong, 2021; Li, 2022). The MBWA Framework emphasizes the connection of 3D-spatial modeling of work, work methods, and temporal patterns of work; this will allow for a fundamental understanding of the relationships between workspaces, work patterns and underlying biomechanical load patterns without requiring observations. In addition, by modeling the workspace and work patterns as a function of work standards and requirements, it is possible to predict potential risks of a job proactively. Leveraging this framework to produce an ergonomic tool will both allow existing workers to self-assess for potential risk, but also allow employers to predict the cost of entry (monetary and equipment) for future remote workers. Taking the type of work and work requirements alongside key spatial and temporal information informs exertion patterns, and in turn WMSD risks (Figure 4.1). Key temporal factors and spatial factors must be identified to build up the model.

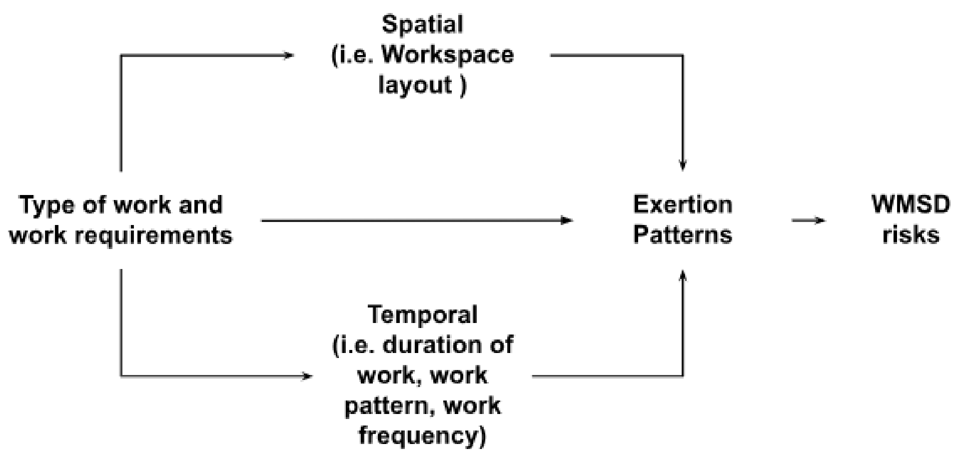


Figure 4.1: Model-based Work Assessment framework to building spatial-temporal model of work

4.1.3 Spatial Factors

The spatial layout of the workspace is a determining factor for how the worker interacts with their environment. Different configurations of space changes posture, reach locations and distances, and underlying doses experienced by the worker's physiological systems (Armstrong et al., 1993). Nearly all common observation based ergonomic assessment methods key in on the postural relationship of the worker and their environment, showing the importance of worker posture (David, 2005). Many studies have shown that altering workspace layouts will change how the individuals would interact with it. Different layouts for tools and relevant work materials will constrain how far workers are required to move. The spatial constraint then determines required posture and required force patterns (Ulin et al., 1993; Armstrong et al., 1986). For office work, positioning of keyboards, mice, monitors, and other accessories have all been shown to be related to fatigue, demonstrating the importance of identifying spatial layout patterns in our tool (Huang, 1999). Lastly, due to WFH workers being able to choose their work environment, the type of workspace chosen, and the frequency of workspace change must also be considered. Thus, the key factors included to describe spatial factors in this study are: equipment layout, posture in relationship to workspace, frequency of posture change, and frequency of workspace change (Table 4.1). Using this conclusion, questions are designed to understand how a worker interacts with their equipment throughout the day, and how that changes their posture throughout the day.

4.1.4 Temporal Factors

Load patterns have been shown to play a significant role in worker productivity, muscle fatigue, and worker discomfort; key temporal factors that impact the worker include work pacing, duration of work, and frequency of breaks (Wells et al., 2007; Rohmert, 1973; Potvin, 2012). However, it is still an aspect not included in many of the commonly used observation methods (David, 2005). A key to understanding the temporal relationship is to look at the exposure and dosage that causes physiological responses within the worker and how fast individuals' physiological systems can recover from work - the dose-response model; work standards and requirements determine the type of movement required by the muscle, and in turn disturbs the internal state of the individuals (Armstrong et al., 1993). To build up a temporal model of remote work, the work standards (duration and types of tasks) for a worker's day must be established. Key details of a worker's day and work patterns are also important to capture. Intermittent breaks have proven beneficial for worker fatigue (Claudon et al., 2020; Potvin, 2012; Mathiassen & Winkel, 1991; ACGIH 2018). Higher duty cycle with increased work pace along with high levels of repetition is often also associated with increased incidence of WMSDs (Latko et al., 1999; Silverstein et al., 1986). Lastly, temporal posture patterns (i.e., how long individuals spend in different postures) can change the required force for a given task due to changing the relevant kinematic chain and significantly impact fatigue (Armstrong et al., 1986). When analyzing remote work, the factors chosen to build up the temporal model are: workday length, work tasks, work task durations, work task pace, temporal posture patterns, frequency of breaks, and duration of breaks (Table 4.1). With these factors as a focus, questions were designed to identify how the WFH employees interact with their work throughout the day – how long they spend doing different tasks, and how long they maintain certain postures. This differentiates this self-reporting tool from previous tools by capturing the totality of the temporal relationship between worker and work for a work day.

4.1.5 MBWA Framework for Remote work

Both the spatial and temporal aspects of work can be informed by the type of work an individual performs, and what the work requirements for each remote workday calls for. Thus, building out a spatial and temporal model requires identifying contributing factors that describe the workspace layout, duration and schedule of work, and the type of work. This will allow for modeling of work-rest periods, movement patterns, and exertion patterns with respect to a worker's physical work environment. Coupling this with published data on forces experienced in common office tasks, an estimation of ergonomic risk can be created. Key factors related are identified and listed in Table 4.1 and integrated into the MBWA framework shown in Figure 4.2. It should be noted that individual factors (such as age and anthropometry) are also needed for spatial modeling and exertion capabilities.

Table 4.1: Various factors for model input

Type of work and work requirements	**Spatial (i.e. Workspace layout)**	**Temporal (i.e. work patterns)**	**Exertion patterns**
Type of work tasks	Equipment layout	Frequency of breaks	Frequency of exertions
Work tools	Worker posture in relation to workstation	Duration of breaks	Body part/segment
	Frequency of posture change	Workday length	Force
	Frequency of workspace change	Work task duration	
		Postural patterns	
		Pace of work	

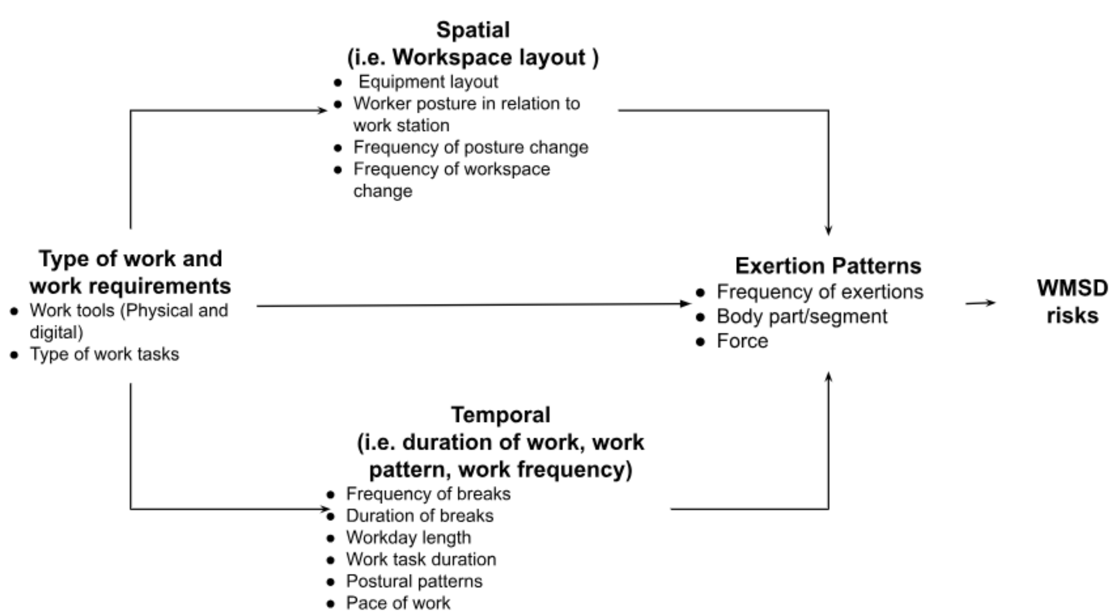


Figure 4.2: MBWA Framework with specific remote work factors

4.1.6 Tool Development

One of the main assumptions for ergonomic assessment for WFH work is that the worker will be self-assessing autonomously. For this reason, it is important that the assessment requires minimal to no training and is intuitive. The approach taken was to evaluate existing ergonomic tools through the lens of administering it in a remote or hybrid work setting while being able to address the various factors listed in Table 4.1. Seven commonly used tools were selected for our study (Joshi & Deshpande, 2019; Lowe & Dempsey, 2019). Due to our scope being focused mainly on WFH office work, we did not expect much lifting, so tools designed specifically for industrial workplaces or focused on lower body work (such as the NIOSH lifting equation or ACGIH TLV for lifting) or inaccessible for the remote worker (such as biomechanical or digital human modeling), were not evaluated in this study. Lastly, ROSA was included in this assessment as that tool was specifically designed for office work; while not heavily represented in the field, for this study it was important to consider. The tools assessed in this study were: RULA, REBA, SI, OWAS, OCRA, QEC, ACGIH TLV HAL, and ROSA (Table 4.2).

Table 4.2: Popular ergonomic tools and key characteristics (adopted from David, 2005) split into spatial, temporal, and exertion patterns that inform inputs into the MBWA framework

	Spatial Patterns			**Temporal Patterns**			**Exertion Patterns**
Tool	**Body Part**	**Posture**	**Dynamics**	**Work Duration**	**Repetition**	**Duty Cycle**	**Force**
REBA (Hignett and McAtamney 2000)	Whole Body	Wrist, lower arm, upper arm, neck, trunk, leg variable cats.	No	No	Activity score increased if static >1 minute, repeated >4 times/min or very large movements	No	Load/Force <5kg, 5-10kg, >10kg, shock

RULA (McAtamney & Corlett 1993)	Upper limb & Torso	Wrist, lower arm, upper arm, neck, trunk, variable categories	No	No	Static > 1 min or repeated >4/min	No	Loads <2kg, 2-10kg (intermittent or static/repeated), >10kg
Strain Index (Garg, 2017)	Hand Wrist	Yes	Very slow; slow; fair; fast; very fast	Yes	Yes	Yes	Yes
OWAS (Karhu, Kansi et al. 1977; Karhu, Harkonen et al. 1981)	Shoulders, neck, back, lower extremity	% time in various posture categories	No	No	No	% time in various posture categories	No
OCRA (Occhipinti 1998; Colombini 1998)	Upper limb	Yes			Yes	Yes	Yes
QEC	Upper limb	Yes		Yes	No	No	Yes
ACGIH TLV for HAL ACGIH (2022)	Hands, wrist, forearm	Professional judgment	Speed of motion	> 4hrs	Observer & rate (0-10) OR freq & duty cycle equation	0-100%	Score 0-10; rate, biomech calcs, psychophysics, instrumentations
ROSA (Sonne et al., 2012a)	Upper limb, trunk	Yes	Static/Dynamic	Yes	No	No	No

Table 4.2 adopts previous work done by G.C. David, which categorizes each of the tools by the relevant body part, and observational methods; to comprehensively describe the mechanical exposures of physical work, three dimensions must be considered: the level and intensity of work, repetitiveness, and duration of exertions (David, 2005). The goal of an assessment for remote workers is that a novice must be able to cover all of the factors listed in Table 4.1, while also being easily accessible for self-assessment. Coupling this with the factors identified in Table 4.1, suitable tools that

can categorize and quantify each of those factors are shown in Table 4.3. While many existing tools have sections that are capable of identifying key factors, it is important to note that this new tool incorporates many new factors that relate to work pace, work scheduling, and work environment. In addition, with all of these factors being self-reporting, this presents a unique challenge as all the remote workers will have slightly different work patterns and work preferences.

Table 4.3: Identified factors from MBWA Framework with applicable tools that can describe each factor through the lens of Remote work. If there are no existing tools that can inform of the necessary factors, new items are created to address those factors.

Type of work and work requirements		**Spatial (i.e. Workspace layout)**		**Temporal (i.e. work patterns)**		**Exertion patterns**	
Tool	***Factors informed***	***Tool***	***Factors informed***	***Tool***	***Factors informed***	***Tool***	***Factors informed***
N/A – new items created	Type of work tasks	ROSA	Equipment layout	N/A – new items created	Frequency of breaks	RULA SI OCRA ACGIH TLV for HAL	Frequency of exertions
N/A – new items created	Work tools	RULA ROSA SI	Worker posture in relation to work station	N/A – new items created	Duration of breaks	RULA SI OCRA ACGIH TLV for HAL	Body part/segment
		N/A – new items created	Frequency of posture change	N/A – new items created	Workday length	RULA SI	Force

						OCRA ACGIH TLV for HAL	
		N/A – new items created	Frequency of workspace change	SI QEC ROSA ACGIH TLV for HAL	Work task duration		
				SI QEC ROSA ACGIH TLV for HAL	Postural patterns		
				SI ACGIH TLV for HAL	Pace of work		

A questionnaire was developed adopting aspects from various tools listed in Table 4.3 that address spatial, temporal, or exertion factors. Items that previous tools did not specifically cover were also added in order to gain a more holistic picture of each remote worker's individual habits and work behaviors (such as work tasks and break behaviors and patterns). Additional items regarding an individuals' demographics were also included. A copy of the Remote Ergonomic Self-Assessment Tool can be found in Appendix C.

Following the piloting of the survey, a focus group was recruited with the goal of understanding what parts of the survey worked well, as well as gain insight for key themes for ergonomic concerns from WFH workers. A copy of the focus group interview script can be found in Appendix D.

4.2 Methods

4.2.1 Remote Ergonomic Self-Assessment Tool (REST) recruitment

Participants (n = 38) were adults (age 18+) who self-identified as being employed full-time and currently working remotely, at least one day per week. We employed purposive sampling for this study, utilizing an online recruitment pool (N > 83,000) managed by a large University in the Midwest of the United States. The REST was adapted into an online questionnaire interface using Qualtrics that was accessible both using a web browser (either computer or mobile based). After participant selection, each participant was sent a direct link to an online survey using the Qualtrics research interface. Prior to recruitment we received approval from our University's Institutional Review Board under the exempt status. The average time for completion among participants was less than 20 minutes. Upon completion, participants were sent a $10 gift card in the mail.

4.2.2 Focus group recruitment

From the participant pool that completed the survey, we then conducted n=1 semi-structured virtual focus group with n=6 participants using the Zoom platform. The focus group interview was performed with the intention to understand how users perceived the tool, as well as develop themes for improvements for future iterations of the tool.

Participants were purposively recruited using the MICHR participant pool and contingent upon their participation in the pilot survey for our remote work ergonomic self-assessment tool. Therefore, participants all self-identified as being employed full-time and working remotely at least one day per week. Participants worked in a variety of industries such as library science, academic research, and health research, and consulting. Informed consent forms were signed and returned to the research team prior to the focus group. Participants were mailed $40 as a token of appreciation upon completion of the focus group.

4.3 Analysis

4.3.1 REST analysis

In this first iteration of piloting the REST, no validated scoring system has been established. Initial scoring approaches were borrowed from various other ergonomic tools; for example, poorer postures would garner a higher score, and the higher cumulative score the more at risk an individual worker would be.

The specific scores calculated from the REST are as follows: six items contributing to the Spatial Factors category, six items contributing to the Temporal Factors category, and two questions contributing to the Exertion category (Table 4.4). The scoring ranges for each of these categories as well as the descriptive statistics are shown in Tables 4.5-4.8.

Items that contributed to the temporal factors included Work duration, Average perceived pace, breaks. For Average perceived pace over the day, participants were asked to self-rate the perceived rate of work for various tasks that they performed over a remote workday. This score was the average of all the perceived pace of different tasks that each individual indicated. Each participant also had a break score - which was how frequently they were able to take breaks, as well as how long their breaks were. Additionally, the type of break (if they stayed in the same location, or changed up their routine) was considered. A high break score would indicate a poor break pattern.

The Spatial Factors category comprised the physical layout of an individuals' work environment, and included questions pertaining to their equipment, and reach. An equipment score was calculated based on a participant's relative positioning of their equipment - for example a poorly set up monitor requiring a lot of head turn would garner a higher score; seating in a poor posture would garner a higher score. A reach score was calculated based on how far and how frequently an individual would be required to move their arms to complete daily tasks.

Lastly, individuals were asked about their exertion levels using various tools throughout the day, which falls under the Exertion category. An additional outcome variable, Average Perceived Exertion, was also calculated. Individuals were asked to rate different tasks that they perform throughout the day and how taxing each different task is.

Table 4.4: Contributing scores for each factor from MBWA framework

	Spatial Factors (n=6)	Temporal Factors (n=6)	Exertion (n=2)
Contributing scores and questions informing each score	• Equipment (peripherals and seating) Score (Q16, 17, 20, 21, 30) • Reach Score (Q24)	• Work Duration (Q4) • Average Pace (Q7)	• Perceived Exertion (Q 22, 23)

		• Break score (Q8, 25, 26, 27, 28)	

The questions were given in either multiple choice format, or in matrix format. Each major category (Spatial, Temporal, and Exertion) were normalized to contribute thirty points to the total Combined Score. In this current scoring method, the range of possible combined score outcomes ranges from zero to ninety.

4.3.2 Focus group analysis

The Focus group discussion session was transcribed using the Zoom transcription and then corrected for errors by the research staff. Transcripts were then thematically coded independently by 2 members on the research team. Codes and emergent themes were then discussed and compared. Any disagreements between coders were discussed and a mutually agreed upon outcome was determined.

4.4 Results

4.4.1 REST Scoring

In the initial piloting of the REST, a total of 38 responses were gathered. Excluding the individuals who did not meet study criteria, or failed the attention check question, a total of 33 (Male = 9) full responses were analyzed. The scores across all of the three major contributing categories of Spatial, Temporal, and Exertion were first calculated using the questions under those categories. The scores from each of these three major categories are shown in Tables 4.5-4.7. A total score from this tool was then calculated Table 4.8; overall, the sample population that we surveyed had a combined score of 35.29

and a standard deviation of 6.89. It should be noted that some participants failed to answer every single question in the survey, which resulted in some of the scores having lower than 33 total responses.

Table 4.5: Spatial scores with each contributing factor normalized to a 10 point scale, with the Spatial category contributing 30 points

Spatial (6 items)	Theoretical Min	Theoretical Max	Observed Min	Observed Max	Mean (SD)
Peripherals Score (2 items) n=31	0	10	0	10	2.42 (2.36)
Seating Score (3 items) n=32	0	10	1.11	10	5.24 (2.37)
Reach Score (1 item) n=31	0	10	0	10	2.74 (2.29)

Table 4.6: Temporal scores with each contributing factor normalized to a 10 point scale, with the Spatial category contributing 30 points

Temporal (6 items)	Theoretical Min	Theoretical Max	Observed Min	Observed Max	Mean (SD)
Breaks (4 items) n=32	0	10	2.23	9.53	5.25 (1.64)
Pace (1 item) n=32	0	10	1.67	8.5	5.40 (1.84)
Total Work duration (1 item) n=33	0	10	2.5	10	7.20 (1.85)

Table 4.7: Exertion scores with each contributing factor normalized to a 10 point scale, with the Spatial category contributing 30 points

Exertion (2 items)	Theoretical Min	Theoretical Max	Observed Min	Observed Max	Mean (SD)
Tool use (2 items) n=29	0	30	0	25.16	7.24 (5.35)

Table 4.8: Combined scores for REST

	Theoretical min	Theoretical max	Min	Max	Mean (SD)
Combined score (n=24)	0	90	21.20	51.73	35.29 (6.89)

Key correlations between all of the contributing factors were examined and shown in Table 4.9. Average perceived exertion was also included as an outcome variable, and correlations calculated between it and the other factors. A few specific correlations that were significant ($p < 0.05$) or low levels of significance ($0.05 < p < 0.10$) are listed below. There was a moderate and highly significant ($p < 0.02$) correlation between the Combined Score of the tool and the demographic variable of Income ($r = -0.48$). There was also a moderate level of correlation at low significance ($p = 0.059$) between the Combined Score and Age ($r = -0.39$). In terms of the overall Combined Score of the tool, there were moderate levels of correlation ($r = 0.62$) at high significance ($p < 0.001$) for pace, and a high level of correlation ($r = 0.80$) at high significance ($p < 0.001$) for tool exertion. There was also a moderate correlation ($r = 0.60$) between the outcome variable "Average Perceived Exertion" and the Combined Score. There was a moderate correlation ($r = -0.47$) between chair and age at high significance ($p < 0.01$). There was a Low correlation ($r = 0.20$) between breaks and gender at high significance ($p = 0.026$). There was a moderate correlation ($r = -0.33$) between breaks and peripherals at low significance ($p = 0.08$). There was a moderate correlation ($r = -0.34$) between breaks and reach at low significance levels ($p = 0.06$).

Table 4.9: Correlations between individual sub factors from different categories - significant correlations are highlighted and bolded, low significance correlations (0.05 < p < 0.10) are highlighted

			Demographic Variables			Spatial Variables			Temporal Variables			Exertion Variable	
		Combined score	Age	Gender	Income	Peripheral	Chair	Reach	Break	Pace	Duration	Tool Exertion	Perceived Exertion
Combined score													
Demographics	Age	-0.39 (0.059)											
	Gender	0.28 (0.19)	-0.29 (0.10)										
	Income	**-0.48 (0.018)**	0.29 (0.10)	-0.22 (0.21)									
Spatial	Peripheral	0.14 (0.50)	-0.21 (0.25)	0.15 (0.42)	0.02 (0.92)								
	Chair	-0.03 (0.88)	**-0.47 (0.007)**	0.28 (0.12)	-0.03 (0.85)	0.07 (0.72)							
	Reach	0.33 (0.11)	0.14 (0.44)	0.12 (0.52)	-0.13 (0.49)	0.20 (0.30)	0.01 (0.94)						
Temporal	Break	0.09 (0.69)	0.05 (0.78)	**0.20 (0.026)**	0.19 (0.31)	-0.33 (0.08)	-0.08 (0.68)	-0.34 (0.06)					
	Pace	**0.62 (0.001)**	-0.21 (0.26)	-0.04 (0.84)	-0.28 (0.12)	0.10 (0.59)	0.00 (0.99)	0.20 (0.29)	0.00 (0.99)				
	Duration	0.09 (0.66)	0.29 (0.10)	-0.01 (0.96)	0.08 (0.64)	-0.22 (0.23)	-0.10 (0.59)	-0.02 (0.92)	0.23 (0.21)	-0.06 (0.76)			
Exertion	Tool Exertion	**0.80 (<0.001)**	-0.33 (0.08)	0.17 (0.38)	-0.37 (0.051)	0.02 (0.91)	-0.28 (0.14)	0.03 (0.87)	0.10 (0.61)	0.27 (0.16)	0.07 (0.72)		
	Avg Perceived Exertion	**0.60 (0.002)**	-0.32 (0.068)	0.18 (0.31)	-0.32 (0.073)	0.05 (0.79)	-0.19 (0.30)	0.12 (0.51)	0.13 (0.48)	0.22 (0.22)	0.02 (0.92)	**0.67 (<0.001)**	

An one-way ANOVA was also performed between three key demographic groupings - Gender, Income class (high vs low), and Age range (high vs low) - and the resulting Combined score of our tool. The results of the ANOVA tests are shown in Table 4.10.

Table 4.10: ANOVA from 3 demographics groupings

		Mean (SD)	F Stats
Gender	Male (n=7)	32.36 (3.85)	F = 1.86 (1,22) , p = 0.19, η^2= 0.078
	Female (n=17)	36.50 (7.58)	
Income	High (n=19)	33.64 (5.37)	F=6.54 (1, 22), p = 0.018*, η^2= 0.229, Power = 0.041
	Low (n=5)	41.59 (8.98)	
Age	Older (n=10)	32.18 (6.32)	F= 3.96 (1,22), p = 0.059, η^2= 0.152, power = 0.11
	Younger (n=14)	37.52 (6.60)	

4.4.2 Focus Group

Participants (n=6) participated in a virtual focus group which lasted approximately 90 minutes. Participants' ages ranged from 30-66. Participants were predominantly female (n=5) and the racial composition of our sample was White (n=3); Black (n=2); and Asian (n=1). Each participant had previously completed our survey and had indicated willingness to be contacted for future data collection related to our study. Participants worked in industries such as library science, laboratory management, research administration, community outreach and project management. Number of days worked remotely ranged from 1 day per week to 5 days per week. The focus group was led by a member of the research team and two other members of the research team were present but off camera and audio in order to take notes. Participants answered a range of questions related to work environment and equipment, work behaviors, attitudes towards remote work, physical health and activity and barriers to productivity. Several themes emerged from this discussion.

First, **the environment impacted participants' physical wellbeing and ability to use appropriate ergonomic equipment**. When one participant was asked about what sorts of ergonomic improvements could be made in her home office she spoke about how her seating options at home were limited and she could feel the impact physically. She said,

> "In terms of seating, I feel like that would be the best option, in terms of improvement. But I actually don't have a space to put a chair so…that's not available to me…Every time I stand up my hip hurts, and I'm like this chair sucks."

Another participant indicated that even though there was the option and resources for an ergonomic setup in her home office, the space belonged to her partner which precluded her from using it. She stated,

> "My partner also works from home, and he has the downstairs basement setup. He's got 3 monitors. He's got everything going on. The ergonomic chair, the desk that's up. But like it's difficult - his job would take precedence…There's no reason that if we have that setup that I would be using it."

Second, **employer provision of equipment and/or resources** was a primary predictor of whether or not the participant had adequate equipment. For instance one participant indicated that the cost of ergonomic equipment was prohibitive unless the employer could provide the equipment. He stated,

> "I think people have figured out their way of adapting you know to circle back around to one of your early questions that creates inclusion and equity issues right? As you know, people only have good setups, because they had the resources to do that…We argued a lot when we decided to go hybrid from fully remote, particularly at [my organization]. Do we need to expand everybody's computer budgets? You've got an office setup *and* a home setup."

A second participant agreed and indicated that she had worked in several places over her career and some employers were much more willing to provide employees with ergonomic equipment than others. She said,

> "I've spent my 30 year career moving all over the United States, and I will say that [my current employer] is more willing to do things ergonomically and provide it [than others], you know? My budget doesn't really have an 'ergonomic' line item in there or I'm blowing my 'office supplies' [line item] out. But everything that I asked for, you know it's yes… versus some of the other places where it's

like, Oh, no! If you want a special chair you'll need to go buy it yourself." Another participant continued, "And ergonomic chairs are expensive!"

Third, all participants indicated that the **flexibility afforded by the ability to work remotely** was the primary benefit to working remotely/hybrid. One participant discussed how she has been able to maximize her overall productivity since moving to a hybrid work schedule. She said,

> "I'm able to take breaks in between. If I have Zoom meetings like today I have another meeting at 1:30 pm. So, after I'm done with you, I have errands I have to do. I'm kind of taking myself away, and then I'll be refreshed. I'm ready to go back, and you feel like you've accomplished [something].

Another participant agreed and referred to these types of breaks as "strategic breaks." She went on to describe how the flexibility of remote work schedules has allowed her new opportunities to spend time with her child. She stated,

> "Sometimes I'm the one dropping off my son [at school] and just to be a part of that while he is young [is important to me]. So I usually wake up a little bit earlier. I can look at emails and kind of get things started for the day and then drop him off. So it allows intentional breaks that are meaningful to me."

These were just a few of the emergent themes which highlighted the impact of remote work on overall well-being of remote workers as well as indicated areas for improvement and opportunities that could be addressed by our new self-assessment tool.

4.5 Discussion & Future work

One of the key questions asked in the survey was regarding the Average Perceived Exertion of workers when performing their work-related tasks throughout the day. It was hypothesized that this Average Perceived Exertion would be a good outcome variable and would correlate highly with the net Combined Score from combining Spatial, Temporal, and Tool Exertion factors. When treating Average perceived exertion as an outcome variable, it correlates highly with the overall combined score supporting the use of Average Perceived Exertion as an outcome variable. This is in line with previous research on self-rated perceived exertion as it has been shown to be a reliable predictor compared to physiological responses to exertion (Stamford, 1976; Borg, 1990; Snook et al., 1966). Beyond physical exertion, self-rated exertion has also shown to be a good indicator of office work comfort, and upper body postures (Lindegard et al., 2012). There was also a strong and significant level of correlation between Average Perceived Exertion and tool exertion - suggesting that what contributes most to worker fatigue comes from any tool usage, and less from the Spatial and Temporal Factors.

There was a low level of correlation between pace and average perceived exertion ($r = 0.22$) with no statistical significance. However, this might be deceptive as there are spatial factors, and temporal factors that correlate moderately with the Combined score at a significant or low significance level. Combined score is mostly correlated with pace and exertion. This suggests that the combined score really is most influenced by pace and tool exertion with average perceived exertion only serving as a good outcome variable for the “Exertion” sub-section of the tool.

With regards to the relationship between pace of work and the resulting Combined Score, there was a moderate to high level of correlation ($r = 0.60$, $p < 0.01$). This suggests that the pace of work for different work tasks is closely related to worker's fatigue and long-term risk. This is consistent with existing work studying worker fatigue - frequency and work done per unit time all show up in different ergonomic tools (ACGIH TLV, 2021; Radwin, 2015; McAtamney, 1993; Moore, 1995; Garg, 2017). Pace in of itself may not be a comprehensive measure of the "busy-ness" of a worker. Additional questions may target broader terms relating to work and borrow some concepts from the Job-Strain Model such as the amount of job demand compared to worker capacity for different tasks (Karasek, 1979). Future iterations of the tool will incorporate more questions regarding pace, and different aspects of work pacing and frequency given its importance in this current study, as well as in previous work (Table 4.11).

There was correlation observed at moderate levels between Combined Score and the demographic scores of Age and Income. This suggests that the individuals who were in a lower income level experienced more cumulative fatigue from their work. This may be due to workers with lower incomes being more likely to put in more hours to try to get ahead. Another explanation of this gap may be due to a digital divide and material divide, where individuals with lower income and lower employer support may have less access for specialized tools needed to make work less easy - such as access to physical tools such as ergonomic chairs and devices, or digital tools such as reliable internet access and specialized software (Lai et al., 2021, Van Deursen et al., 2019). Their work may also include more physically demanding activities such as data entry or drafting and writing. This is supported with a moderate correlation at low significance ($r=-0.37$, $p = 0.051$)

between Exertion and Income. This suggests that the amount of exertion does differ between individuals from high- and low-income classes. Lastly, this may be due to lower income workers having less work flexibility and being less able to spend time away from work (Reid et al., 2001; Nakata et al., 2011).

The correlation between Combined score and Age implies that younger individuals are at higher fatigue risks. This might be due to the fact that younger workers typically have less control over their work time and work hours (Paterson et al., 2015). The data also alludes to this; there is a low level of correlation ($r = 0.29$) between work duration and age groups ($p = 0.10$). While not statistically significant, it does imply that younger workers are spending more of the day performing work-related tasks. Younger individuals may also be performing more labor-intensive tasks - there was a moderate level of correlation at low significance ($r = -0.33$, $p = 0.08$) between Exertion and age. In addition, older workers may benefit from being long-time “survivors” and have more experience optimizing the work that they perform (Saksvik et al., 2011). From a physiological standpoint, older adults were found to have better endurance and less fatigability when performing isometric exertions - this translates well to the sustained postures often associated with office work (Enoka, 2012; Hunter et al., 2004).

In terms of the correlation between the various contributing factors, we noticed that there were moderate levels of correlation between Peripheral Score and Breaks, as well as Reach score and Breaks. This suggests that more breaks are needed when needing to perform tasks with poor peripherals set up, and larger amounts of reach tasks. There was also a moderate and significant level of correlation between age and Chair score (r

= -0.47, p = 0.007). This may suggest that older workers are more cognizant of seating posture.

When designing the tool, there was a hypothesis that the amount of breaks a worker takes would have a large impact on fatigue factors. However, there was no correlation between breaks and Combined score. However, during our focus group, one of the key themes and takeaways was that having the ability to introduce breaks into the day made a big difference in perceived fatigue. This discrepancy between the survey result and the focus group results may be due to the fact that when responding to questions relating to work duration, the respondents would factor in the breaks that they are taking. Future iterations of the tool may focus more on the types of breaks, and the ability for location change, more so than just directly about breaks (Table 4.11).

Our survey did also include questions relating to the cost of entry for healthy home ergonomics including potential financial support from employers. While we have not performed an analysis on that portion of our data, our initial results from Tool Exertion score suggests that equipment does play a large factor in the overall combined score, which is also reflected in previous work. For example, the type of armrests and peripherals significantly changes perceived fatigue (Huang, 1999). Future iterations of the tool may expand upon the types of tools used for work-related tasks, placing a focus on whether ergonomic tools were available (Table 4.11).

Table 4.11: Additions and items for future iterations of the REST

	Spatial Factors	Temporal Factors	Exertion
Current limitations	1. No correlation between chair score and combined score. However, focus	1. There was a large correlation between Pace and the	1. There was high correlation between physical

	group participants identified lack of ergonomic chairs as a big issue. 2. The current tool was not able to capture the importance of switching between different types of workspaces (home office, informal desk such as dining table, or lounge areas such as sofas and beds). However, the focus group suggested that the ability to alter their workstations was important.	Combined score - this along with previous work suggests that pacing is a key item in predicting physical outcomes 2. There was no correlation between breaks & the combined score. However, the focus group reflected that having breaks throughout the day was important 3. The current tool does a poor job identifying the duration of time spent on each different work task - due to there being many options of tasks, and the intervals being 0-2hr, the total sum of task duration often exceeded the hours in a work day.	tool exertion and the combined score, but the current tool only has two items. 2. The current tool only asks about physical exertion when using different tools, however, there is no contextualizing against a worker's capabilities.
Updates for Future	1. To better address chair usage, the instrument will include more specific questions about current chair usage in the context of different work stations. o Does layout allow for specialized chairs o How do informal workspace (sofa or lounge) seating compare to more formal workspace (home office, dining room) seating o Adjustability and customizability of chairs (seat back, cushion, etc)	1. Items regarding physical job demand & busy-ness and relating it to an individual's capabilities 2. Items regarding availability and accessibility of ergonomic tools (ie chairs & peripherals) o Pacing of different tasks and how well individuals can keep up 3. The future scoring method of the tool	1. Add in additional items regarding the specific type of tool (arm rest, mouse, monitor, keyboard) and the perceived exertion of those tools. 2. Add in questions regarding the physical job demand in terms of exertion & relating it to an individual's capabilities

	○ More minute measurements of physical relationship to workstation (for example: distance between head and monitor) 2. Additional questions will be added asking about perceived physical comfort in different workspaces ○ Do different workstations lend better to certain types of tasks due to material and tool limitations	would differentiate between various aspects of breaks - break quality, break type, and if the break alleviated any fatigue. 4. Future iterations of this tool will ask about time spent on any given task as a percentage, and make sure that the total percentage cannot exceed 100%	

Upon review we identified an oversight in our approach to assessing the total time participants spent on various daily tasks (Figure 4.3). Participants were presented with six potential response options ranging from N/A to >8 hours per day with a 2-hour time range for each response option. Because the range of potential time spent on each task was set at two-hour intervals, the cumulative sum of an individual's total task times often exceeded the expected duration of a work day.

During your typical remote work day, which of the following tasks are you engaged in and for what duration?

	N/A	0-2hr	2-4hr	4-6hr	6-8hr	>8hr
Data entry	○	○	○	○	○	○
Emails	○	○	○	○	○	○
Meetings (Virtual via computer)	○	○	○	○	○	○
Writing/Drawing (Pen/pencil/tablet)	○	○	○	○	○	○
Coding	○	○	○	○	○	○
Reading	○	○	○	○	○	○
Administrative tasks	○	○	○	○	○	○
Phone calls (Not via computer - physical phone)	○	○	○	○	○	○
Chat based meetings (Slack, Microsoft Team)	○	○	○	○	○	○
Writing via typing	○	○	○	○	○	○
Other	○	○	○	○	○	○

Figure 4.3: Task & Task duration - due to the responses being at 2 hour intervals, total daily task time often exceeded 8hrs

Similarly, there were questions presented with the intention of being included for contributing to Spatial Factor scoring that contextually may not work the best. For example, we had asked whether a participant had a home office (with monitor, peripherals, office chair and other accessories) or primarily worked in a casual setting (lounging, sitting at a couch, or working on a dining table). The initial plan was to weigh a formal home office positively, and to penalize informal work settings. However, many of the participants indicated that they may switch between work settings frequently, thus potentially negating any negative impact of working a short period of time in an informal location without proper equipment. This was supported by our focus group interview as well. Many shared the sentiment that the physical equipment available may not have been as important as being able to work in multiple locations. One participant mentioned the benefit of choosing work location depending on type of work (if doing more intensive tasks such as typing, a desk may be useful; but if just reading, the task could be done while lounging outside).

Through our initial pilot deployment of this tool, we identified some high-level themes of the ergonomics of remote workers. This work has also opened up many avenues for future work. This tool requires more iterative deployment to ensure that useful information is being collected from every question. One major drawback of the current iteration of the tool is the lack of minute specificity in our modeling. Scores were calculated relying on an individuals' self-report; individuals' ratings of exertion and pace may not match what a trained observer would rate. In addition, different individuals may produce different ratings for the same type of task. Future iterations may also include fields where individuals can upload images of their workstations to help create a more realistic 3D workspace model. A summary of changes to future iterations of the tool is listed in Table 4.11. To address the issue of self-report variation, validation is required with observational data. Future studies could involve bringing in people into a mock office set up so that we can look at the differences of work behaviors in a mock office environment versus a mock home set up.

4.6 Conclusion

With the findings from our pilot survey results, as well as the focus group interviews, further refinement can result in a simple self-assessment tool for WFH workers. Specific recommendations going forward include adding in additional questions to address the temporal factor of Pace. Many existing metrics include frequency or pace as a key measure. In addition, questions targeting broader measures of Job Demand will also be introduced. Initially, it was hypothesized that the temporal factor of breaks would have significant correlation with the overall score; however, the survey data did not support this. The Focus group did indicate that having flexibility in breaks was important. In future iterations, the duration of breaks will be less focused on, rather new questions involving the type of breaks, and the quality of breaks will be introduced. In terms of the exertion modeling, currently only two questions are asked about individual exertion. Additional questions will be included to improve the robustness of this variable (Table 4.11). Lastly, in the current iteration of our tool, the spatial layout of the workstation didn't seem to have much correlation with the resulting scores. This may be due to the fact that the ability to change workspaces has more of an impact. Future iterations of the tool may focus more on postural change depending on workspace change. Ultimately, this study demonstrates the feasibility of the application of using the MBWA framework in designing the REST.

References

Armstrong, T. J. (2021, May). CAD and MODAPTS Models for Assessing Localized Fatigue. In Congress of the International Ergonomics Association (pp. 682-687). Cham: Springer International Publishing.

Armstrong, T. J., Radwin, R. G., Hansen, D. J., & Kennedy, K. W. (1986). Repetitive trauma disorders: job evaluation and design. Human factors, 28(3), 325-336.

Armstrong, T. J., Buckle, P., Fine, L. J., Hagberg, M., Jonsson, B., Kilbom, A., ... & Viikari-Juntura, E. R. (1993). A conceptual model for work-related neck and upper-limb musculoskeletal disorders. Scandinavian journal of work, environment & health, 73-84.

Bailenson, J. N. (2021). Nonverbal overload: A theoretical argument for the causes of Zoom fatigue.

Bergefurt, L., Appel-Meulenbroek, R., Maris, C., Arentze, T., Weijs-Perrée, M., & de Kort, Y. (2023). The influence of distractions of the home-work environment on mental health during the COVID-19 pandemic. Ergonomics, 66(1), 16-33.

Borg, G. (1990). Psychophysical scaling with applications in physical work and the perception of exertion. Scandinavian journal of work, environment & health, 55-58.

Chang, A. (2021, March 18). Working from home takes a physical toll - and companies are trying to profit from that. Los Angeles Times. https://www.latimes.com/business/story/2021-03-18/work-from-home-pain

Claudon, L., Desbrosses, K., Gilles, M. A., Pichené-Houard, A., Remy, O., & Wild, P. (2020). Temporal leeway: can it help to reduce biomechanical load for older workers performing repetitive light assembly tasks?. Applied Ergonomics, 86, 103081.

Colombini, D. (1998). "An observational method for classifying exposure to repetitive movements of the upper limbs." Ergonomics 41(9): 1261-89.

Cropley, M., Weidenstedt, L., Leick, B., & Sütterlin, S. (2022). Working from home during lockdown: The association between rest breaks and well-being. Ergonomics, 1-11.

Dempsey, P. G., Lowe, B. D., & Jones, E. (2019). An international survey of tools and methods used by certified ergonomics professionals. In Proceedings of the 20th Congress of the International Ergonomics Association (IEA 2018) Volume III: Musculoskeletal Disorders 20 (pp. 223-230). Springer International Publishing.

David, G. C. (2005). Ergonomic methods for assessing exposure to risk factors for work-related musculoskeletal disorders. Occupational medicine, 55(3), 190-199.

David, G., Woods, V., Li, G., & Buckle, P. (2008). The development of the Quick Exposure Check (QEC) for assessing exposure to risk factors for work-related musculoskeletal disorders. Applied ergonomics, 39(1), 57-69.

Enoka, R. M. (2012). Muscle fatigue–from motor units to clinical symptoms. Journal of biomechanics, 45(3), 427-433.

Galanti, T., Guidetti, G., Mazzei, E., Zappalà, S., & Toscano, F. (2021). Work from home during the COVID-19 outbreak: The impact on employees' remote work productivity, engagement, and stress. Journal of occupational and environmental medicine, 63(7), e426.

Garg, A., Moore, J. S., & Kapellusch, J. M. (2017). The Revised Strain Index: an improved upper extremity exposure assessment model. Ergonomics, 60(7), 912-922.

Hignett, S. and L. McAtamney (2000). "Rapid entire body assessment (REBA)." Applied Ergonomics 31(2): 201-5.

Huang, I. W. (1999). Effects of keyboards, armrests, and alternating keying positions on subjective discomfort and preferences among data entry operators. University of Michigan.

Hunter, S. K., Critchlow, A., & Enoka, R. M. (2004). Influence of aging on sex differences in muscle fatigability. Journal of Applied Physiology, 97(5), 1723-1732.

Jones, T., & Kumar, S. (2010). Comparison of ergonomic risk assessment output in four sawmill jobs. International Journal of Occupational safety and ergonomics, 16(1), 105-111.

Joshi, M., & Deshpande, V. (2019). A systematic review of comparative studies on ergonomic assessment techniques. International Journal of Industrial Ergonomics, 74, 102865.

Karasek Jr, R. A. (1979). Job demands, job decision latitude, and mental strain: Implications for job redesign. Administrative science quarterly, 285-308.

Karhu, O., P. Kansi, et al. (1977). "Correcting working postures in industry: A practical method for analysis." Applied Ergonomics 8: 199-201.

Karhu, O., Härkönen, R., Sorvali, P., & Vepsäläinen, P. (1981). Observing working postures in industry: Examples of OWAS application. Applied ergonomics, 12(1), 13-17.

Kong, Y. K., Lee, S. Y., Lee, K. S., & Kim, D. M. (2018). Comparisons of ergonomic evaluation tools (ALLA, RULA, REBA and OWAS) for farm work. International journal of occupational safety and ergonomics, 24(2), 218-223.

Lai, J., & Widmar, N. O. (2021). Revisiting the digital divide in the COVID-19 era. Applied economic perspectives and policy, 43(1), 458-464.

Latko, W. A., Armstrong, T. J., Franzblau, A., Ulin, S. S., Werner, R. A., & Albers, J. W. (1999). Cross-sectional study of the relationship between repetitive work and the prevalence of upper limb musculoskeletal disorders. American journal of industrial medicine, 36(2), 248-259.

Li, Y., & Armstrong, T. J. (2022, September). Model Based Approach of Integrating Spatial and Temporal Tools compared to traditional Time Studies. In Proceedings of the Human Factors and Ergonomics Society Annual Meeting (Vol. 66, No. 1, pp. 646-650). Sage CA: Los Angeles, CA: SAGE Publications.

Lindegård, A., Wahlström, J., Hagberg, M., Vilhelmsson, R., Toomingas, A., & Wigaeus Tornqvist, E. (2012). Perceived exertion, comfort and working technique in professional computer users and associations with the incidence of neck and upper extremity symptoms. BMC musculoskeletal disorders, 13(1), 1-8.

Lowe, B. D., Dempsey, P. G., & Jones, E. M. (2019). Ergonomics assessment methods used by ergonomics professionals. Applied ergonomics, 81, 102882.

Mathiassen, S. E., & Winkel, J. (1991). Quantifying variation in physical load using exposure-vs-time data. Ergonomics, 34(12), 1455-1468.

McAtamney, L., & Corlett, E. N. (1993). RULA: a survey method for the investigation of work-related upper limb disorders. Applied ergonomics, 24(2), 91-99.

Moore, J. S. and A. Garg (1995). "The Strain Index: a proposed method to analyze jobs for risk of distal upper extremity disorders." Am Ind Hyg Assoc J 56(5): 443-58.

Nakata, A. (2011). Effects of long work hours and poor sleep characteristics on workplace injury among full-time male employees of small-and medium-scale businesses. Journal of Sleep Research, 20(4), 576-584.

Occhipinti, E. (1998). OCRA: a concise index for the assessment of exposure to repetitive movements of the upper limbs. Ergonomics, 41(9), 1290-1311.

Parker, K., Horowitz, J. M., & Minkin, R. (2020). How the coronavirus outbreak has–and hasn't–changed the way Americans work. Pew Research Center, 9.

Parker, K., Horowitz, J., & Minkin, R. (2022). COVID-19 pandemic continues to reshape work in America. Pew Research Center.

Paterson, J. L., Clarkson, L., Rainbird, S., Etherton, H., & Blewett, V. (2015). Occupational fatigue and other health and safety issues for young Australian workers: an exploratory mixed methods study. Industrial health, 53(3), 293-299.

Prasad, K. D. V., Vaidya, R. W., & Mangipudi, M. R. (2020). Effect of occupational stress and remote working on psychological well-being of employees: An empirical analysis during covid-19 pandemic concerning information technology industry in hyderabad. Indian Journal of Commerce and Management Studies, 11(2), 1-13.

Potvin, J. R. (2012). Predicting maximum acceptable efforts for repetitive tasks: an equation based on duty cycle. Human factors, 54(2), 175-188.

Radwin, R. G., Azari, D. P., Lindstrom, M. J., Ulin, S. S., Armstrong, T. J., & Rempel, D. (2015). A frequency–duty cycle equation for the ACGIH hand activity level. Ergonomics, 58(2), 173-183.

Rempel, D. (2018). 1631c Recent changes to the ACGIH hand activity level TLV.

Reid, K., & Dawson, D. (2001). Comparing performance on a simulated 12 hour shift rotation in young and older subjects. Occupational and Environmental Medicine, 58(1), 58-62.

Rohmert, W. (1973). Problems of determination of rest allowances Part 2: Determining rest allowances in different human tasks. Applied ergonomics, 4(3), 158-162.

Saksvik, I. B., Bjorvatn, B., Hetland, H., Sandal, G. M., & Pallesen, S. (2011). Individual differences in tolerance to shift work–a systematic review. Sleep medicine reviews, 15(4), 221-235.

Silverstein, B. A., Fine, L. J., & Armstrong, T. J. (1986). Hand wrist cumulative trauma disorders in industry. Occupational and Environmental Medicine, 43(11), 779-784.

Snook, S. H., & Irvine, C. H. (1966). The evaluation of physical tasks in industry. American Industrial Hygiene Association Journal, 27(3), 228-233.

Sonne, M., Villalta, D. L., & Andrews, D. M. (2012a). Development and evaluation of an office ergonomic risk checklist: ROSA–Rapid office strain assessment. Applied ergonomics, 43(1), 98-108.

Sonne, M., & Andrews, D. M. (2012b). The Rapid Office Strain Assessment (ROSA): Validity of online worker self-assessments and the relationship to worker discomfort. Occupational Ergonomics, 10(3), 83-101.

Stamford, B. A. (1976). Validity and reliability of subjective ratings of perceived exertion during work. Ergonomics, 19(1), 53-60.

Streeter, J., Roche, M., & Friedlander, A. (2021). From Bad to Worse: The Impact of Work-From-Home on Sedentary Behaviors and Exercising.

Ulin, S. S., Armstrong, T. J., Snook, S. H., & Monroe-Keyserling, W. (1993). Examination of the effect of tool mass and work postures on perceived exertion for a screw driving task. International Journal of Industrial Ergonomics, 12(1-2), 105-115.

Van Deursen, A. J., & Van Dijk, J. A. (2019). The first-level digital divide shifts from inequalities in physical access to inequalities in material access. New media & society, 21(2), 354-375.

Wells, R., Mathiassen, S. E., Medbo, L., & Winkel, J. (2007). Time—a key issue for musculoskeletal health and manufacturing. Applied Ergonomics, 38(6), 733-744.

Williams, N. (2017). The Borg rating of perceived exertion (RPE) scale. Occupational Medicine, 67(5), 404-405.

CHAPTER 5

Summary, Conclusions, and Future Applications

The objective of this dissertation was to formulate, implement, and demonstrate the flexibility and applicability of the Model-Based Work Assessment Framework for proactive work assessment. Chapter 1 focused on the development of the Model through integration of various spatial, temporal, and exertion factors. The key objectives of Chapters 2-4 were to apply the Model in various applications. First to examine the accuracy predicting work steps and elements and to establish various work patterns. Following, exertion patterns were folded into the model to demonstrate how a framework can define normal work and how to control for exertions experienced by the worker. This was done through a comparative analysis of using the MBWA approach in predicting motion patterns as well as exposures for workers as compared to traditional observation-based approaches. In addition, various applications of MBWA in non-traditional work settings were also explored, which illustrates the proactive nature and flexibility of a framework approach.

5.1 Summary of Findings

5.1.1 Objective one: Framework Validation comparing spatial and temporal modeling with time study approach

The first objective was to demonstrate the validity of the Model-Based Work Assessment (MBWA) framework as compared to traditional time-study techniques. This was a study performed in the context of work and job tasks performed involving cyclical tasks in various industrial environments. A total of five different jobs were analyzed varying from tasks involving seated work with shorter cycle times, to tasks that involve larger workspaces with more flexibility of worker movement. A CAD model was constructed of each of these workspaces, and key work locations were identified using the work standards. From there, the necessary workflow patterns were determined, building up from the work standards and work goals. This helped inform what were the upper limb motions necessary for a worker to complete each of these tasks. Using these motion patterns, and the distances from the CAD model, times for each task were produced. The model produced time was then compared from the cycle times produced from traditional time-study methods. From each of these tasks, a total of nine cycles were analyzed per task. The average time for each task was compared to that of the model-predicted times. Overall, in the different jobs that were analyzed, none of the model predicted times deviated from the average observed time-study times by more than 7%. This suggests that overall, the model does well in predicting cycle times. However, it should be noted that while the overall cycle times are predicted well, individual motions in specific use-cases are not predicted as well. These specific use cases happen when the workers are interacting with flexible materials or perform simultaneous motions on the same object.

5.1.2 Objective two: Extend framework application by incorporating exposure-dose indices for fatigue prediction

The key objective of the second study was to close the loop on ergonomic risk estimations using the framework approach. In addition, use case examples were examined to demonstrate the proactive nature of work assessment using the framework approach. Chapter three builds on the work from chapter two and closes the loop incorporating exposure-dose risk estimation. The same videos from Chapter two were further analyzed and exertion patterns were examined using both the Model-based approach, and traditional observational methods. This chapter also demonstrates the proactive nature of applying the framework, offering examples of workflow changes to reduce worker exposure. The model generally did a good job predicting the exposure to the workers; the model predicted duty cycles differing from the observation-based results by ~9-21%. However, the model did also routinely underpredict the duration of exposure. This may be due to the limitations of using MODAPTS for temporal modeling as MODAPTS frequently does not adjust for movement times when a worker is interacting with heavy loads. MODAPTS for the most part only predicts times based on the distances or the body parts used; however, when a worker is carrying or interacting with materials, the movement patterns may become constrained. This may also be a result of MODAPTS not having built in allowances; with movement patterns defined by distance and body part, it's hard to add in additional time a worker might need to re-position or adjust certain work objects or tools. This study also suggested various decision rules to adjust and add in those allowances.

5.1.3 Objective three: Demonstrate flexibility of MBWA framework in non-traditional work cases.

Chapter four explores the application of the framework in non-traditional work settings. The MBWA framework was used to develop an online Remote Self-assessment

Tool (REST) for Work from Home (WFH) workers. A mixed-method approach involving a focus group was leveraged to understand the strengths and weaknesses of the first iteration of the REST tool. The MBWA framework was applied to model out key spatial, temporal, and exposure factors that may impact a WFH worker's day-to-day fatigue risks. The tool was developed combining existing validated concepts with new items to fully model the spatial, temporal, and exposure factors. The tool was piloted and the total score, as well as scores from key contributing factors were calculated. It was found that the pace of work (temporal), and the tool use exertion (exertion) were highly correlated with the overall score. This suggests that the tool successfully captured key temporal and exertion factors. However, there was little correlation between the spatial factors and the overall score, suggesting that future iterations need to be more mindful of addressing this aspect of the tool.

5.2 Key contributions - MBWA Framework

The main contribution of this work - the Model-Based Work Assessments approach - allows for work analysis to be done on a wide range of work and job activities without need for observers or to have workers in a work setting. This framework builds up an understanding of the relationship between the worker and the work as a function of the work goals and standards. This is a proactive approach whereas a lot of existing observer based methods are often retrospective studies.

With a proactive approach, the work system design can be modeled using CAD, time systems, and exposure models. This allows for exposure and fatigue assessment to be done in the design phase of many work systems. If the work is inappropriate for workers, then it can be changed and modified during the design phase. This approach also provides a rigorous framework for understanding necessary movement patterns to complete a given task; that means this research can also be applied to future developments to provide contextual understanding of the worker-work interaction. This dissertation currently focuses on the upper limbs (namely hand and wrist). The framework can be further expanded to look at the shoulder and potentially back. In addition, broader applications of the framework can be applied to various domains including manufacturing, medical devices, medical systems, and various consumer productions. Furthermore, data from emerging technologies such as computer vision and IMUs can be integrated and interpreted using the framework.

5.3 MBWA Framework in non-traditional work environments

A pilot study was performed collaborating with practitioners in the Kellogg Eye Center (Appendix E). Work-related musculoskeletal disorders for ophthalmologists is an increasing issue as a majority of practitioners have indicated discomfort or pain (Dhimitri et. al, 2005; Honavar et. al, 2017; Marx, 2012). Ophthalmology practitioners may see over 100 patients weekly for clinical exams, with each exam consisting of a long sequence of steps that vary from case to case (Marx, 2012). Thus, taxonomy was developed following the MBWA framework a) to describe clinical procedures with sufficient detail to review differences among practitioners, b) to examine the relationship between individual technique, spatial and temporal relationships of the workspace for calculating biomechanical risk, and c) to enable practitioners to standardize technique around best practices as well as suggest work changes that can reduce load and risk. Three different examples of ophthalmological exams were recorded for three different practitioners of differing statures. A 3D model of the workspace was created using AutoCAD for the spatial modeling of the workspace. A hierarchical task analysis (HTA) was used to decompose the observed exams into successive levels of detail; this served as the temporal definition of movement patterns within the MBWA framework. The results were then used to perform load pattern and fatigue risk analysis for upper-body limbs using a 3D Static Strength Posture Prediction Tool (3DSSPP) (Chaffin, 2005). Using the 3DSSPP tool as the measure for exposure, we were able to identify key steps during the clinical process that exacerbated awkward postures. Following that, workspace interventions in AutoCAD were suggested, show the strength of designing changes virtually and proactively. Using This demonstrates the wide application domains of using a proactive model-based approach, allowing for minute risks to be understood in less-structured clinical settings.

5.4 MBWA Framework for emerging technologies

A case study (Appendix F) examining the application of the MBWA framework integrates evolving technologies and methodologies to demonstrate model flexibility and broader applications. This case study applies the various components of the Model-Base Work Assessment framework on existing video work tasks with the goal of incorporating evolving techniques used for ergonomic exposure assessment - namely computer vision (Greene, 2019; Azari, 2019; Li, 2019).

The approach to this case study utilizes the Spatial, Temporal, Ergonomic, and Force model developed in the previous studies and apply the Model-Based work assessment framework in a real-world setting. Ergonomic exposure assessments was performed using the Model-based approach as well as using time study approach; those outcomes will then be supplemented with computer vision analysis.

The computer vision tool was used to track link movements, with initial analysis focused on the hand and wrist (Cao, 2019). The computer vision aids in creating a kinematic profile of movement patterns of the worker that can predict ergonomic exposure and various risks when used together with the CAD and PTS portion of the MBWA framework.

While the pilot data involving computer vision is limited, when used in conjunction with wearable sensing and traditional motion capture methodologies, a more robust kinematic profile can be created in the laboratory. Combining the kinematic profiles with the MBWA framework creates a structured approach for proactive work analysis. The results of this study should demonstrate the functionality of applying the framework and creating quantifiable metrics of improvements using emerging tools as well as the broader applicability of this approach.

5.5 Limitations & future directions

There are a few key limitations of this work that must be addressed in future work. First, while Chapter Two demonstrated that using a model-based approach for estimating work times, it also showed that in some use cases, the PTS does not do a good job estimating movement times. This lends naturally for future research to do a more nuanced analysis on specific movement patterns across more varied jobs to identify additional taxonomy updates that might be needed for the temporal modeling portion of the framework. In addition, current work focuses on using MODAPTS as the PTS for temporal modeling. MODAPTS was chosen for this dissertation due to it being widely used because of its simplicity and ease of training for industrial professionals. However, for additional rigor, other PTS might be considered - for example MTM which has more nuanced movements defined.

Another fundamental consideration that needs to be addressed is that the MBWA framework is only as good as the different input models that are used to build up the framework. For example, in spatial modeling a simple sketch may be used as the input, but that would be much less detailed and a weaker analysis method as compared to AutoCAD. Likewise, when considering exposure-dosing for the worker, the MBWA produced ergonomic risk assessment is only as good as the input. For the current research, the exposure examined in Chapter 3 was duty cycles calculated using ACGIH TLV. It should be noted that other tools can also be used for inputs.

Chapter four aimed to explore applying the framework approach in designing, producing, and analyzing for ergonomic risk among Work from Home workers. Using the framework approach, key factors regarding the worker work relationship for WFH individuals were identified, and a first iteration of a Remote Self-Assessment Tool was produced. However, this tool still lacks validation. Additional work would need to compare the worker self-assessment with additional context of the different tasks that make up a WFH individual's workday. Future studies in this area could involve laboratory-based studies where workers are working in a simulated home environment; the predicted workload from the MBWA approach could then be compared to what is observed in the simulated home environment.

Lastly, the main directions for future research lies in the flexibility of the MBWA approach. Various case studies have been conducted applying the MBWA framework to non-traditional and non-cyclical tasks such as healthcare. By taking a systematic approach building up understanding of the work as a function of the work standards and goals, even highly variable work such as clinical exams or surgeries can be reduced down to predictable motion patterns. This type of approach can also lay the foundation and context for applying direct measurement techniques such as computer vision methods, and physiological response measures.

5.6 Concluding remarks

This research has formulated and formalized a Model-based Work Assessment Framework that can analyze work based on work goals and work standards. This allows for a rigorous approach to understanding the underlying relationships between workers and their work. In addition, using this framework approach, exposures can be understood as a function of different movement patterns driven by the work standards. This dissertation also applied the Model-based approach in a number of non-cyclical work settings, demonstrating that this mental model and this type of approach can be applied to many different domains. By understanding the relationship between the work goals, the workspaces, the movement patterns, and the exposures associated with movements proactively, this framework also allows for workflow and job standards to be optimized prior to inserting the worker into the system. Future domain applications of this framework can include manufacturing, healthcare, medical devices and systems, and transportation.

References:

Azari, D. P., Hu, Y. H., Miller, B. L., Le, B. V., & Radwin, R. G. (2019). Using surgeon hand motions to predict surgical maneuvers. Human factors, 61(8), 1326-1339.

Cao, Z., Hidalgo, G., Simon, T., Wei, S. E., & Sheikh, Y. (2019). OpenPose: realtime multi-person 2D pose estimation using Part Affinity Fields. IEEE transactions on pattern analysis and machine intelligence, 43(1), 172-186.

Chaffin, D. B. (2005). 3D SSPP (Static Strength Prediction Program), version 5.04. Ann Arbor (MI): University of Michigan.

Dhimitri, K. C., McGwin Jr, G., McNeal, S. F., Lee, P., Morse, P. A., Patterson, M., ... & Marx, J. L. (2005). Symptoms of musculoskeletal disorders in ophthalmologists. American journal of ophthalmology, 139(1), 179-181.

Greene, R. L., Hu, Y. H., Difranco, N., Wang, X., Lu, M. L., Bao, S., ... & Radwin, R. G. (2019). Predicting sagittal plane lifting postures from image bounding box dimensions. Human factors, 61(1), 64-77.

Honavar, S. G. (2017). Head up, heels down, posture perfect: Ergonomics for an ophthalmologist. Indian journal of ophthalmology, 65(8), 647.

Li, Y., Wolf, M., Kulkarni, A., Bell, J., Chang, J., Nimunkar, A., & Radwin, R. G. (2019, November). Quantification of In Situ Tremor in Microscopic Surgery. In Proceedings of the Human Factors and Ergonomics Society Annual Meeting (Vol. 63, No. 1, pp. 1067-1068). Sage CA: Los Angeles, CA: SAGE Publications.

Marx, J. L. (2012). Ergonomics: back to the future. Ophthalmology, 119(2), 211-212.

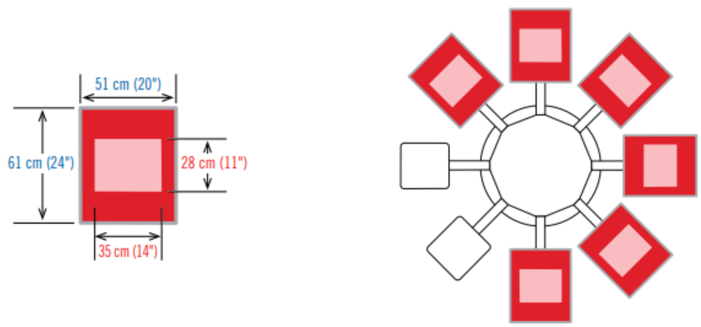
Appendices

APPENDIX A

Example of equipment dimensions from manufacturer

Diamondback L 8/6

Diameter	259 cm (8' 6")
Frame Size	51 x 61 x 4.5 cm (20" x 24" x 1.75")
Maximum Image Area	35 x 28 cm (14" x 11")
Standard Pallet Size	15 x 41 cm (6" x 16") 38 x 41 cm (15" x 16")



Appendix Figure A.1 Machinery used for one of the jobs analyzed (Diamondback T-shirt printing) which allowed for more accurate spatial representation in the CAD model (M & R Printing equipment Inc. Diamondback Series - Automatic Screen Printing Presses, M & R Sales and Services, 2015.).

APPENDIX B

Workflow updates informed by Ergonomic Assessment

											Tw (%MVC≥7%)		∑(time×force)	
n	Element Description	Hand	Motion Code	Freq	Mods	Force	Posture	Population*	Strength*	%MVC	R	L	R	L
1	Move from palm button	R Move	M4	1	4	0.0	open	male, 50th	23.4	0	0	---	0	---
	Get Bracket	Get/Put	G1	1	1	2.3	pinch		23.5	10	1	---	10	
	Move from palm button	L Move	M4	1	4	0.0	open		23.4	0	--	0	---	0
	Get Bolt	Get/Put	G3	1	3	0.0	pinch		23.4	0	--	0	---	0
		Combined	**M4G3**	---	**7**	---	---	---	---	---			---	
2	Move bracket to welder	R Move	M4	1	4	2.3	Pinch		23.4	10	4	---	39	---
		Get/Put	P0H3	1	3	2.3	"		23.4	10	3	---	29	
	Move to previous assembly	L Move	M4	1	4	0.0	"		23.4	0	--	0	---	0
	Get previou assembly	Get/Put	G3	1	3	2.3	"		23.4	10	--	3	---	29
		Combined	**M4G3**	---	**7**	---	---	---	---	---			---	
3	Wait	R Move	H4	1	4	2.3	Pinch		23.4	10	4	---	39	---
		Get/Put		1					23.4	0	0	---	0	
	Move previous assembly to triwall	L Move	M4	1	4	2.3	Pinch		23.4	10	--	4	---	39
	Put previous assembly to triwal	Get/Put	P0	1	0				23.4	0	--	0	---	0
		Combined	**M4P0**	---	**4**	---	---	---	---	---			---	
4	Wait	R Move	H4	1	4	2.3	Pinch		23.4	10	4	---	39	---
		Get/Put		1					23.4	0	0	---	0	
	Move back to welder	L Move	M4	1	4	0.0	Pinch		23.4	0	--	0	---	0
		Get/Put	P0	1	0				23.4	0	--	0	---	0
		Combined	**M4P0**	---	**4**	---	---	---	---	---			---	
5	Align bracket to welder	R Move	M2	1	2	2.3	Pinch		23.4	10	2	---	20	---
		Get/Put	P5	1	5	2.3			23.4	10	5	---	49	
	Align bolt to welder	L Move	M2	1	2	0.0	Pinch		23.4	0	--	0	---	0
		Get/Put	P5	1	5	0.0			23.4	0	--	0	---	0
		Combined	**2x M2P5**	---	14	---	---	---	---	---			---	
6	Move hand to palm button	R Move	M4	1	4	0.0	Open		23.4	0	0	---	0	---
		Get/Put	P0	1	0	0.0	Open		23.4	0	0	---	0	
	Move hand to palm button	L Move	M4	1	4	0.0			23.4	0	--	0	---	0
		Get/Put	P0	1	0	0.0			23.4	0	--	0	---	0
		Combined	M4P0	---	4	---	---	---	---	---			---	
7	Press and hold button	R Move		1	8	3.5			23.4	15	8	---	120	---
		Get/Put		1					23.4	0	0	---	0	
	Press and hold button	L Move		1	8	3.5			23.4	15	--	8	---	120
		Get/Put		1					23.4	0	--	0	---	0
		Combined		---	8	---	---	---	---	---			---	

Appendix Figure B.1: Original workflow derived using MBWA for Assembly welding job

											Tw (%MVC≥7%)		∑(time×force)	
n	Element Description	Hand	Motion Code	Freq	Mods	Force	Posture	Population*	Strength*	%MVC	R	L	R	L
1	Move from button	R Move	M4	1	4	0.0	open	male, 50th	23.4	0	0	---	0	---
		Get/Put	P0	1		0.0	pinch		23.5	0	0	---	0	
	Move from button	L Move	M4	1	4	0.0	open		23.4	0	--	0	---	0
	Get Bolt	Get/Put	G3	1	3	0.0	pinch		23.4	0	--	0	---	0
		Combined	**M4G3**	---	7	---	---	---	---	---			---	
2	Wait	R Move		1			Pinch		23.4	0	0	---	0	---
		Get/Put		1			"		23.4	0	0	---	0	
	Move to previous assembly	L Move	M4	1	4	0.0	"		23.4	0	--	0	---	0
	Get previou assembly	Get/Put	G3	1	3	2.3	"		23.4	10	--	3	---	29
		Combined	**M4G3**	---	7	---	---	---	---	---			---	
3	Get Bracket	R Move	M2	1	2		Pinch		23.4	0	0	---	0	---
		Get/Put	G1	1	1	2.3			23.4	10	1	---	10	
	Move previous assembly to triwall	L Move	M4	1	4	2.3	Pinch		23.4	10	--	4	---	39
	Put previous assembly to triwal	Get/Put	P0	1	0				23.4	0	--	0	---	0
		Combined	**M4P0**	---	4	---	---	---	---	---			---	
4	Move to welder	R Move	M4	1	4	2.3	Pinch		23.4	10	4	---	39	---
		Get/Put	P0	1					23.4	0	0	---	0	
	Move back to welder	L Move	M4	1	4	0.0	Pinch		23.4	0	--	0	---	0
		Get/Put	P0	1	0				23.4	0	--	0	---	0
		Combined	**M4P0**	---	4	---	---	---	---	---			---	
5	Align bracket to welder	R Move	M2	1	2	2.3	Pinch		23.4	10	2	---	20	---
		Get/Put	P5	1	5	2.3			23.4	10	5	---	49	
	Align bolt to welder	L Move	M2	1	2	0.0	Pinch		23.4	0	--	0	---	0
		Get/Put	P5	1	5	0.0			23.4	0	--	0	---	0
		Combined	**2x M2P5**	---	14	---	---	---	---	---			---	
6	Move hand to button	R Move	M4	1	4	0.0	Open		23.4	0	0	---	0	---
		Get/Put	P0	1	0	0.0	Open		23.4	0	0	---	0	
	Move hand to button	L Move	M4	1	4	0.0			23.4	0	--	0	---	0
		Get/Put	P0	1	0	0.0			23.4	0	--	0	---	0
		Combined	M4P0	---	4	---	---	---	---	---			---	
7	Press and hold button	R Move		1	8	3.5			23.4	15	8	---	120	---
		Get/Put		1					23.4	0	0	---	0	
	Press and hold button	L Move		1	8	3.5			23.4	15	--	8	---	120
		Get/Put		1					23.4	0	--	0	---	0
		Combined		---	8	---	---	---	---	---			---	

Appendix Figure B.2: Suggested Updated MODAPTS workflow for Assembly Welding Job

APPENDIX C

Remote Ergonomic Self-Assessment Tool (REST)

Remote Work Ergonomics Self-Assessment

Start of Block: Consent

Consent This survey lasting no longer than 30 minutes. You will be asked to answer questions and provide insight on topics related to technology use, experiences related to work and productivity, and general questions about your well-being. There are no expected direct benefits for taking part in this study. The study's potential for both practical and scientific contributions are significant. Results from this study will inform both supervisors and employees of the potential benefits and challenges related to remote work, productivity, and health.

Upon completion of the survey you will be asked to enter your preferred email and mailing address after which, we will send you a gift card in appreciation of your participation.

If you have questions about this research study, please contact Dr. Jess Francis, jessfran@umich.edu or Yifan Li, lyifan@umich.edu

If you consent to continue with the survey, please select Yes

○ Yes (1)

○ No (2)

Skip To: End of Survey If Consent = No

End of Block: Consent

Start of Block: Screening

D1: AGE What is your age?

○ Under 18 (1)

○ 18 - 24 (2)

○ 25 - 34 (3)

○ 35 - 44 (4)

○ 45 - 54 (5)

○ 55 - 64 (6)

○ 65 - 74 (7)

○ 75 - 84 (8)

○ 85 or older (9)

Skip To: End of Survey If AGE = Under 18

D2: Employment Are you currently employed full-time?

○ Yes (1)

○ No (2)

Skip To: End of Survey If Employment = No

D3: Remote Do you work remotely at least part of the time?

- ○ Yes (1)
- ○ No (2)

Skip To: End of Survey If Remote = No

End of Block: Screening

Start of Block: Demographics & Anthropometry

D4: Education What is the highest level of school you have completed or the highest degree you have received

- ○ Less than high school (1)
- ○ High school/GED (2)
- ○ Some college (3)
- ○ Bachelor's degree or higher (4)

D5: Latinx Do you consider yourself to be Hispanic or Latino

- ○ Yes (1)
- ○ No (2)
- ○ Refused (3)
- ○ Don't know (4)

D6: Ethnicity What race or races do you consider yourself to be? Please select one or more of these categories.

- ☐ White (1)
- ☐ Black/African American (2)
- ☐ American Indian (3)
- ☐ Alaska Native (4)
- ☐ Native Hawaiian (5)
- ☐ Other Pacific Islander (6)
- ☐ Asian (7)
- ☐ Some other race (8)
- ☐ Refused (9)
- ☐ Don't know (10)

D7: Gender Are you male or female?

- ○ Male (1)
- ○ Female (2)
- ○ Other (3)
- ○ Prefer not to answer (4)

D8: Height What is your height in inches? If you are 5ft 4 inches, you would enter 64.

____

D9: Weight What is your weight in pounds?

____

D10: Income What was your entire household income last year, before taxes?

- ◯ < $20,000 (1)
- ◯ $20,000 to $34,999 (2)
- ◯ $35,000 to $49,999 (3)
- ◯ $50,000 to $74,999 (4)
- ◯ $75,000 to $99,999 (5)
- ◯ $100,000 to $149,999 (6)
- ◯ $150,000 to $199,999 (7)
- ◯ $200,000 or more (8)

D11: Marital What is your current marital status?

- ◯ Married or living with partner (1)
- ◯ Widowed (2)
- ◯ Divorced (3)
- ◯ Seperated (4)
- ◯ Never married (5)

D12: Household How many individuals currently live in your household in addition to yourself? Please enter the total number in each age category.

○ A. Total number of household members age 0 to 5 (1) ____

○ B. Total number of household members age 6 to 12 (2) ____

○ C. Total number of household members age 13 to 17 (3) ____

○ D. Total number of household members age 18 or older (4) ____

End of Block: Demographics & Anthropometry

Start of Block: Work & Work Requirements

Work Prompt The questions in this section ask about your current **remote** working arrangements. If you have more than one job, please answer questions as they apply to your *main* job.

Q1: EmploymentDuration How long have you worked in your job?

○ Less than 1 year (1)

○ 1-5 years (2)

○ 6-10 years (3)

○ 10-20 years (4)

○ More than 20 years (5)

Q2: Sector Select the occupation that best describes the kind of work you do in your job

- Architecture and Engineering (1)
- Arts, Design, Entertainment, Sports, and Media (2)
- Building and Grounds Cleaning and Maintenance (3)
- Buisness and Financial Operations (4)
- Computer and Mathematical (5)
- Community and Social Service (6)
- Construction and Extraction (7)
- Education Instruction and Library (8)
- Farming, Fishing, and Forestry (9)
- Food Preparationand Serving Related (10)
- Healthcare Practitioners and Technical (11)
- Healthcare Support (12)
- Installation, Maintenance, and Repair (13)
- Legal (14)
- Life, Physical, and Social Science (15)
- Management (16)
- Material Movement (17)
- Military Specific (18)
- Office and Administrative Support (19)

○ Personal Care and Service (20)

○ Production (21)

○ Protective Service (22)

○ Sales and Related (23)

○ Transportation (24)

○ Other (Please specify): (25)

____

Q3: RemotePercent Approximately what percentage of your work is performed remotely per week?

○ 1-20% (1)

○ 21-40% (2)

○ 41-60% (3)

○ 61-80% (4)

○ 81-100% (5)

Q4: WorkDuration During your typical remote work day, how many hours would you be performing work-related tasks?

- ○ 0-2Hrs (1)
- ○ 2-4Hrs (2)
- ○ 4-6Hrs (3)
- ○ 6-8Hrs (4)
- ○ >8Hrs (5)

Q5: TaskTypeDuration During your typical remote work day, which of the following tasks are you engaged in and for what duration?

	N/A (1)	0-2hr (2)	2-4hr (3)	4-6hr (5)	6-8hr (6)	>8hr (7)
Data entry (1)	○	○	○	○	○	○
Emails (2)	○	○	○	○	○	○
Meetings (Virtual via computer) (3)	○	○	○	○	○	○
Writing/Drawing (Pen/pencil/tablet) (4)	○	○	○	○	○	○
Coding (5)	○	○	○	○	○	○
Reading (6)	○	○	○	○	○	○
Administrative tasks (7)	○	○	○	○	○	○
Phone calls (Not via computer - physical phone) (8)	○	○	○	○	○	○
Chat based meetings (Slack, Microsoft Team) (9)	○	○	○	○	○	○
Writing via typing (12)	○	○	○	○	○	○
Other (13)	○	○	○	○	○	○

Q6: TaskTypeExert During your typical remote work day, what is the perceived exertion (physical effort) for each task you perform where 0 is no exertion, and 5 is a high level of exertion? If a given task is not part of your typical remote work day, please select N/A.

	0 - No Exertion (1)	1 (2)	2 (3)	3 (4)	4 (5)	5 - High Exertion (6)	N/A (7)
Data entry (1)	o	o	o	o	o	o	o
Emails (2)	o	o	o	o	o	o	o
Meetings (Virtual via computer) (3)	o	o	o	o	o	o	o
Writing/Drawing (Pen/pencil/tablet) (4)	o	o	o	o	o	o	o
Coding (5)	o	o	o	o	o	o	o
Reading (6)	o	o	o	o	o	o	o
Administrative tasks (7)	o	o	o	o	o	o	o
Phone calls (Not via computer - physical phone) (8)	o	o	o	o	o	o	o
Chat based meetings (Slack, Microsoft Team) (9)	o	o	o	o	o	o	o
Writing via typing (12)	o	o	o	o	o	o	o
Other (13)	o	o	o	o	o	o	o

Q7: TaskExertPace During your typical remote work day, what is the perceived pace for each task you perform? For example in the "writing via typing" task, a 5 would be constant typing at your fastest typing speed, where 0 would be infrequent typing (tapping a few keys per minute).

	0 - Low Pace (1)	1 (2)	2 (3)	3 (4)	4 (5)	5 - High Pace (6)	N/A (7)
Data entry (1)	o	o	o	o	o	o	o
Emails (2)	o	o	o	o	o	o	o
Meetings (Virtual via computer) (3)	o	o	o	o	o	o	o
Writing/Drawing (Pen/pencil/tablet) (4)	o	o	o	o	o	o	o
Coding (5)	o	o	o	o	o	o	o
Reading (6)	o	o	o	o	o	o	o
Administrative tasks (7)	o	o	o	o	o	o	o
Phone calls (Not via computer - physical phone) (8)	o	o	o	o	o	o	o
Chat based meetings (Slack, Microsoft Team) (9)	o	o	o	o	o	o	o
Writing via typing (12)	o	o	o	o	o	o	o
Other (13)	o	o	o	o	o	o	o

End of Block: Work & Work Requirements

Start of Block: Workspace Layout & Exertion

Q8: WorkEnvChngAblty During the course of your remote work day - are you able to change your workplace environment and work from a different physical location?

- ○ Almost Never (1)
- ○ Sometimes (2)
- ○ Frequently (3)
- ○ Whenever I want (4)

Q9: WorkLayoutDuration During a typical remote work day, what modality of workspace do you use and for approximately how long?

	0 (1)	0-2hrs (2)	2-4hrs (3)	4-6hrs (4)	6-8hrs (5)	>8hrs (6)
Formal home office (i.e. full monitor set up with peripherals) (1)	○	○	○	○	○	○
Informal home office (i.e. Dinner table) (2)	○	○	○	○	○	○
Home lounge (i.e. couch, bed, floor) (3)	○	○	○	○	○	○
Informal external space (i.e. library, coffee shop) (4)	○	○	○	○	○	○
External lounge space (i.e. lawn, park, beach) (5)	○	○	○	○	○	○

Display This Question:

If WorkLayoutDuration != Formal home office (i.e. full monitor set up with peripherals) [0]

Q10: FormalOfficeEquip If you have a Formal home office - what type of equipment do you use?

- ☐ Desktop + Monitor(s) (1)
- ☐ Laptop + Monitor(s) (2)
- ☐ Laptop Keyboard + Trackpad (3)
- ☐ External Keyboard (4)
- ☐ External Mouse (5)
- ☐ Tablet (6)
- ☐ Arm or Wrist Rest (7)

Display This Question:

If WorkLayoutDuration != Formal home office (i.e. full monitor set up with peripherals) [0]

Q11: FormalEquipSource If you have a formal office set up - who provided the start up cost?

- ☐ Myself (1)
- ☐ Employer (2)
- ☐ Other (3) ____

Display This Question:

If WorkLayoutDuration != Informal home office (i.e. Dinner table) [0]

And WorkLayoutDuration != Informal external space (i.e. library, coffee shop) [0]

Q12: InformalOfficeEquip If you work at an informal space (i.e. dinner table, coffee shop) - what type of equipment do you use?

- ☐ Laptop + Monitor(s) (1)
- ☐ Laptop Keyboard + Trackpad (2)
- ☐ External Keyboard (3)
- ☐ External Mouse (4)
- ☐ Tablet (5)
- ☐ Arm or Wrist Rest (6)

Display This Question:

If WorkLayoutDuration != Home lounge (i.e. couch, bed, floor) [0]

And WorkLayoutDuration != External lounge space (i.e. lawn, park, beach) [0]

Q13: LoungeOfficeEquip If you work at in a lounge space (i.e. couches, bed) - what type of equipment do you use?

- ☐ Laptop + Monitor(s) (1)
- ☐ Laptop Keyboard + Trackpad (2)
- ☐ External Keyboard (3)
- ☐ External Mouse (4)
- ☐ Tablet (5)
- ☐ Arm or Wrist Rest (6)

Display This Question:

If FormalOfficeEquip = Arm or Wrist Rest

Or InformalOfficeEquip = Arm or Wrist Rest

Or LoungeOfficeEquip = Arm or Wrist Rest

Q14: ArmRest If you use an arm or wrist rest as part of your work set up, what kind best describes your arm or wrist rest?

- ○ Chair arm rest (1)
- ○ External articulating wrist rest (2)
- ○ Foam (or similar material) wrist rest on table (3)
- ○ Other (4) ____

Q15: EquipSupp How much financial, equipment, or set up assistance have you received through your employer for your remote work?

○ No assistance (1)

○ Some assistance (2)

○ A lot of assistance (3)

Q16: ChairHt During seated work, which of the following best describes your chair height?

Image adopted from ROSA

○ A (1)

○ B (2)

○ C (3)

○ D (4)

○ E (5)

Q17: ChairPan During seated work, which of the following best describes your seat pan?

Image adopted from ROSA

- A (1)
- B (2)
- C (3)

Q18: ChairHtMeasure Roughly how high off the ground in inches is your seat height in inches?

____

Q19: AttenChck Please select "Somewhat agree" to show that you are paying attention

- Strongly disagree (1)
- Somewhat disagree (2)
- Neither agree nor disagree (3)
- Somewhat agree (4)
- Strongly agree (5)

Q20: MonitorHt When engaging in computer work that involves a monitor, is the top of the monitor:

- ○ Far below eye level (1)
- ○ Below eye level (2)
- ○ At eye level (3)
- ○ Above eye level (4)
- ○ Far above eye level (5)

Q21: MonitorWdth When engaging in computer work that involves a monitor, does the monitor(s) usage require significant head turning in order to see the entire monitor(s)?

- ○ Almost never (1)
- ○ Sometimes (2)
- ○ About half the time (3)
- ○ Most of the time (4)

Q22: MouseUse If you use an external mouse, how much travel is required for your typical tasks?

- ○ Very little ((1)
- ○ A little (2-4 inches per move) (2)
- ○ A moderate amount (4-6 inches per move) (3)
- ○ A large amount (6-12 inches per move) (4)

Q23: KeyboardExert If you engage in frequent typing tasks, how taxing are the typing tasks?

- ○ Minimal (1)
- ○ A little (2)
- ○ Moderate (3)
- ○ Somewhat high (4)
- ○ Extremely taxing (5)

Q24: Reach During your typical remote work day, how often do you perform reach tasks (for example to grasp mouse, reach for water, reach for various equipment). If you consistently use your mouse with your arm extended, that be considered a frequent reach with long distance.

	Not frequent (1)	Somewhat frequent (2)	Very frequent (3)
Reach distances < 6in (1)	○	○	○
Reach distances 6-12 inches (2)	○	○	○
Reach distances > 12 inches (3)	○	○	○

End of Block: Workspace Layout & Exertion

Start of Block: Work Schedule

Q25: BreakFreq During your remote work day, how frequently do you take breaks?

○ Every fifteen minutes or less (1)

○ Every thirty minutes (2)

○ Hourly (3)

○ Every two hours (4)

○ Every three hours (5)

○ Every four hours (6)

○ No breaks (7)

Q26: BreakDuration During your remote work day, when you take a break, how long would your breaks last?

- ◯ <5 minutes (1)
- ◯ 5-10 minutes (2)
- ◯ 10-20 minutes (3)
- ◯ 20-30 minutes (4)
- ◯ >30 minutes (5)

Q27: BreakType During your remote work day, when you take a break, are you more likely to:

- ◯ Physically leave workstation (1)
- ◯ Consume entertainment or performing other tasks while at workstation (2)
- ◯ Perform home tasks (laundry, dishes, other chores) that require physical exertion (3)

Q28: PostChange During your work day, are you able to significantly change your work posture - for example changing from seated to standing, or from seated to prone postures?

- Every fifteen minutes or less (1)
- Every thirty minutes (2)
- Hourly (3)
- Every two hours (4)
- Every three hours (5)
- Every four hours (6)
- N/A (7)

Q29: StandingWrk If you engage in remote work in a standing posture, roughly how long do you spend standing cumulatively each day?

- 0-2hr (1)
- 2-4hr (2)
- 4-6hr (3)
- 6-8hr (4)
- >8hr (5)
- N/A (6)

Q30: SeatWrk If you engage in remote work in a sitting, roughly how long do you spend in a "poor posture?"
Examples shown below

- ○ 0-2hr (1)
- ○ 2-4hr (2)
- ○ 4-6hr (3)
- ○ 6-8hr (4)
- ○ >8hr (5)
- ○ N/A (6)

End of Block: Work Schedule

Start of Block: Compensation

Name Name (First, Last):

____

MailAddress Mailing Address

____

City City:

____

Zip Zip Code

____

End of Block: Compensation

APPENDIX D

Focus Group Interview Script

Introduce myself/study as well as human factors and ergonomics at a high level.

Introduction - The key objective of our study is to develop a self-assessment tool that remote and hybrid workers can use independently to evaluate for potential ergonomic risk and physical well-being. The approach that we are taking is to identify potential postural concern, and from there postural pattern concerns.

Re-state consent form.

Demographics review:

- Could you tell us your age, field/industry of work, how long have you been at your current position, and remote work percentage

- How often do you do remote work
  - When you're not working remotely, do you have an office space
  - Compare and contrast home vs office space

- Do you work same hours remote versus in office

Environment

Equipment questions:

- Could you describe your typical work configuration (For example I use a monitor, and external mouse when at my "home office," but use only my laptop when lounging or at a coffee shop) with a focus on the equipment used.
    - Where do you guys work, what type of chairs, desk, tables etc
    - Do you experience any fatigue or pain when using these equipment

- Do you notice differences between using home office equipment versus having a dedicated in-person office?

- If you had any assistance with setting up your home office from your employer, could you share that experience?

- Do you use specialized ergonomic chairs or other equipment?

- Do you use standing desks? Do those help with posture?

Movement patterns and exertions

Tasks:

- In the survey, we tried to identify what types of key tasks are typically associated with a remote work day, do you think the choices given were sufficient?
  - What are "other" work tasks that may not have been captured by the given choices?
- Do you perform the same type of tasks at home versus in the office
- For the tasks that you perform during your remote work day, which ones takes the most exertions? Could you describe what that looks like in terms of exertion as well as time spent doing the task?

- In the survey we also asked about the pacing of the tasks you may perform, could you describe which tasks are the highest pacing and describe what that might look like in terms of duration and pacing?
  - For the pacing question, it was intended to capture movement frequency, where a lower number (1 or 2) might mean a few movement patterns per minute, where a higher number might mean constant movement (for example constantly typing for long durations (>20-30 minutes).
- Do you have to perform reach tasks frequently?

Temporal patterns

Breaks:

- Are you able to change your workspace location and physically move around? Could you describe your routine?
- Are you able to take frequent breaks? Describe your breaks and what you typically do during your breaks

Overall:

- What type of fatigue or discomfort or pain do you have when working remotely?
  - Postural
  - Break frequency
  - Work pace

- How do you feel in general about having remote work
  - Stress and cognitive factors

- How do you think your employer could have supported you better?

- Did taking the survey help you think more critically about what type of factors to be aware of during remote work?

- What type of follow up and additional help would be useful to help with worker wellbeing?
    - Training modules for better spatial and temporal awareness?

Wrap up:

- Anything else regarding your perception of remote worker health that we haven't covered today

APPENDIX E

Hierarchical Task Analysis of Ophthalmology Clinical Exam for identifying Biomechanic Risks

Abstract:

A taxonomy was developed a) to describe clinical procedures with sufficient detail to review differences among practitioners, b) to examine the relationship between individual technique, spatial and temporal relationships of the workspace for calculating biomechanical risk, and c) to enable practitioners to standardize technique around best practices as well as suggest work changes that can reduce load and risk. Three different examples of ophthalmological exams were recorded for three different practitioners of differing statures. A hierarchical task analysis (HTA) was used to decompose the observed exams into successive levels of detail. The results were then used to perform load pattern and fatigue risk analysis for upper-body limbs. Analysis of these selected cases using the proposed taxonomy demonstrates how even routine ophthalmologic clinical exams pose fatigue risks for the practitioners.

Introduction:

This work aims to develop a taxonomy that can be used to a) to describe clinical procedures with sufficient detail to review differences among practitioners, b) to examine the relationship between individual technique, spatial and temporal relationships of the workspace for calculating biomechanical risk, and c) to enable practitioners to standardize technique around best practices as well as suggest work changes that can reduce load and risk.

Work-related musculoskeletal disorders for ophthalmologists is an increasing issue as a majority of practitioners have indicated discomfort or pain (Dhimitri et. al, 2005; Honavar et. al, 2017; Marx, 2012). Ophthalmology practitioners may see over 100 patients weekly for clinical exams, with each exam consisting of a long sequence of steps that vary from case to case (Marx, 2012). In some cases, these variations are required due to the specific condition of each patient. In other cases, these variations may be due to personal preference. However, it is still uncertain what exact methods are best practice within a clinical setting.

Thus, a taxonomy describing clinical procedures is needed. Much of the existing focus for creating taxonomies and task analysis for ophthalmology has been focused on surgical training (Chee et. al, 2015; Lorch et. al, 2017). There has yet to be much work focused on the execution of day-to-day clinical examinations that ophthalmology practitioners would perform many times a day. This study aims to focus on the clinical side and introduce a standardized taxonomy for clinical exams - namely the slit lamp exam.

Due to the fixed nature of the equipment for the slit lamp exam, there is a very constrained spatial relationship between the practitioner and the patient. The practitioners may often find themselves in a less than ideal posture (Figure E1). In addition, due to the nature of the exams, there are a lot of opportunities for sustained upper limb postures that could be fatigue risks. Thus by developing a taxonomy that breaks down the procedure step-by-step, we can examine the relation between different individual movement patterns by combining spatial and temporal requirements of the task, and perform strength and fatigue analysis to understand ergonomic risk.

Methods

A taxonomy was developed using HTA methodology that has been described in past studies (MacKenzie et. al, 2001; Sarker et. al, 2008; Stanton, 2006; Yu et. al, 2010). This particular study is focused on the Slit Lamp exam performed within ophthalmology clinics. Practitioners may perform upwards of 100 patients weekly, and as many as 40 slit lamp exams in a single day. The slit lamp exam is a commonly performed clinical procedure where the practitioner lines up a vertical microscope with the patient's eye for examination. The patient has their head resting on a chin and forehead rest, with the practitioner positioned opposite the patient (Figure E.1). Development of a taxonomy was done iteratively with feedback from a practitioner collaborator. Analysis were done on demonstration videos recorded on a handheld camera where the practitioners were asked to show their movement patterns during the slit lamp procedure with another collaborator acting as the patient.

Appendix Figure E.1: Slit lamp exam example with a tall female practitioner

Observed practitioners

The practitioners for this study consisted of a convenient sample group. Video recordings were created by a practitioner collaborator using a hand held camera. A total of three informal example cases were recorded of practitioners of different statures (5th percentile female, 95th percentile female, and 50th percentile male); they were all right hand dominant. All three practitioners were free of any existing musculoskeletal disorders. Additional measurements of tools and equipment were taken during a visit to the clinic.

Taxonomy development

The proposed taxonomy includes three basic levels that comprise the overall slit lamp exam: 1) Tasks, 2) Subtasks, 3) Elements. Each level of the HTA includes a group of tasks. In level 1 - Tasks, the actions are “prepare patient,” “prepare equipment,” and “examine patient.” Each of these tasks subsequently includes a series of subtasks. Examples include “position slit lamp,” “adjust lamp intensity,” and “examine eye.” Each subtask is defined by an objective and has defined start and stop times. These subtasks can further be decomposed into elements. Elements are also defined by an objective, but timing may be grouped together to describe an objective performed by two hands in parallel. Each element has a set of attributes that further helps describe an instance of that element. Attributes include: method, work object, tool, material, environmental conditions, ergonomic concerns, and timing.

The focus was to identify elements of the clinical exam that potentially posed fatigue risks. Strength and fatigue analysis were then performed on postures of identified elements to identify ergonomic risk.

Results

From the HTA analysis, three major tasks were identified for the Slit Lamp Exam: 1) Prepare Patient, 2) Prepare Equipment, and 3) Examine Patient.

The first two major tasks are performed by support staff while the third task is conducted by the ophthalmologist. The breakdown of the first two tasks into subtasks is shown in Table E.1. Table E.2 shows results from the breakdown of Task 3 - Examine patients - which were performed by practitioners and had notable differences of subtask order and number of subtasks. Task 3 and subsequent subtasks for each individual practitioner was further divided into elements along with other key attributes shown in Table E.3, E.4, and E.5. The key attributes of this analysis are ergonomic concerns and the total time for each work element. The attributes that contribute to the ergonomic concerns are the work object, work tools, and work methods as these ultimately determine the movement patterns of the upper limbs. In particular, sustained postures of the upper limb was a concern and durations where practitioners maintained such a posture were identified.

Appendix Table E.1: Tasks 1 and 2 along with corresponding subtasks

Task	**Subtask**
1 Prepare patient	1.1 Remove accessories (glasses/spectacles)
	1.2 Position patient
2 Prepare equipment	2.1 Position patient chair
	2.2 Set lighting intensity
	2.3 Set magnification
	2.4 Set diopter for oculars
	2.5 Set ocular pupillary distance
	2.6 Unlock joystick

Appendix Table E.2: Task 3 - subtasks performed by each practitioner

Task 3 - Examine Patient		
Tall Female	**Short Female**	**Tall Male**
3.1 Position slit lamp table	3.1 Position slit lamp table	3.1 Position slit lamp table
3.2 Position chair	3.2 Position chair	3.2 Turn on light beam
3.3 Turn on light beam	3.3 Position slit lamp	3.3 Position chair
3.4 Examine right eye	3.4 Turn on light beam	3.4 Examine right eye
3.5 Examine left eye	3.5 Examine right eye	3.5 Examine left eye
3.6 Examine right eye with lens	3.6 Examine left eye	3.6 Examine right eye with lens
3.7 Examine left eye with lens	3.7 Examine right eye with optical lens	3.7 Examine left eye with lens
3.8 Turn off light beam	3.8 Examine left eye with optical lens	3.8 Turn off light beam
	3.9 Turn off light beam	

Appendix Table E.3: Task 3 (Examine Patient) breakdown with Key attributes for 95th percentile Female

Task 3 - Examine Patient		**Task Attributes**				
Subtask	**Element**	**Work object**	**Methods**	**Tools**	**Ergonomic concerns**	**Total Time (s)**
3.1 Position slit lamp table		Slit lamp table	Place both hands on the outsides of the slit lamp table			3
3.2 Position chair		Chair	Move back rest using right hand. Slide chair forward using legs			3.6
3.3 Turn on light		Slit lamp table	Flip embedded switch with left hand			1.5
3.4 Examine right eye	3.4.1 Position Lamp	Slit lamp	Place left hand on the left dial		Left Arm extended (12.9s)	12.9
	3.4.2 Inspect right eye	Patient (right eye)		Slit lamp oculars		
	3.4.3 Adjust intensity	Slit lamp	Turn intensity dial using left hand			
	3.4.4 Position slit lamp	Slit lamp	Place left hand on the left dial			
	3.4.5 Inspect right eye	Patient (right eye)		Slit lamp oculars		
3.5 Examine left eye	3.5.1 Position slit lamp	Slit lamp	Place left hand on the left dial		Right Arm extended (17.6s)	17.6
	3.5.2 Inspect left eye	Patient (left eye)		Slit lamp oculars		

	3.5.3 Adjust intensity	Slit lamp	Turn intensity dial using left hand			
3.6 Examine right eye with optical lens	3.6.1 Retrieve optical lens	Optical lens	Retrieve optical lens from slit lamp table with left hand			2.2
	3.6.2 Position slit lamp	Slit lamp	Move joystick with right hand	Slit lamp oculars		1.2
	3.6.3 Position arm	Doctor (left arm)	Raise arm and position left hand near patient face		Left Arm - Arm extended (27.2s) Right Hand - Repetitive fine motions	27.2
	3.6.4 Align optical lens	Optical lens	Alight optical lens with light beam and slit lamp oculars	Slit lamp oculars		
	3.6.5 Position slit lamp	Slit lamp	Move/turn joystick using right hand	Slit lamp oculars		
	3.6.6 Inspect right eye	Patient (right eye)		Slit lamp oculars		
	3.6.7 Adjust intensity	Slit lamp	Turn intensity dial using left hand			
3.7 Examine left eye with optical lens	3.7.1 Retrieve optical lens	Optical lens	Retrieve optical lens from slit lamp table with right hand			1.2
	3.7.2 Position slit lamp	Slit lamp	Move joystick with left hand	Slit lamp oculars		7
	3.7.3 Position arm	Doctor (right arm)	Raise arm and position right hand near patient face		Right Arm extended (30.8s) Left hand Repetitive fine motions	30.8
	3.7.4 Align optical lens	Optical lens	Alight optical lens with light beam and slit lamp oculars	Slit lamp oculars		
	3.7.5 Position slit lamp	Slit lamp	Move/turn joystick using left hand	Slit lamp oculars		
	3.7.6 Inspect left eye	Patient (left eye)		Slit lamp oculars		
3.8 Turn off light		Slit lamp table	Press switch using left hand			1.7

Appendix Table E.4: Task 3 (Examine Patient) breakdown with Key attributes for 5th percentile Female

Task 3 - Examine Patient		Task Attributes				
Subtask	**Element**	**Work object**	**Methods**	**Tools**	**Ergonomic concerns**	**Total Time (s)**
3.1 Position chair		Chair	Move back rest using right hand. Slide chair forward using legs			5
3.2 Position slit lamp table		Slit lamp table	Place both hands on the outsides of the slit lamp table			19.8
3.3 Position Lamp		Slit lamp	Place left hand on the left dial			8.4
3.4 Turn on light		Slit lamp table	Flip embedded switch with left hand			0.2
3.5 Examine right eye	3.5.1 Position Lamp	Slit lamp	Place left hand on the left dial		Left Arm extended (3s)	3
	3.5.2 Inspect right eye	Patient (right eye)		Slit lamp oculars		
3.6 Examine right eye	3.6.1 Position slit lamp	Slit lamp	Place left hand on the left dial		Right Arm extended (5.9s)	5.9

	3.6.2 Inspect right eye	Patient (right eye)		Slit lamp oculars		
3.7 Examine right eye with optical lens	3.7.1 Retrieve optical lens	Optical lens	Retrieve optical lens from slit lamp table with left hand			9.4
	3.7.2 Position arm	Doctor (left arm)	Raise arm and position left hand near patient face			1.1
	3.7.3 Position slit lamp	Slit lamp	Move joystick with right hand	Slit lamp oculars	Left arm extended (25.1s) Right hand repetitive fine motions	25.1
	3.7.4 Align optical lens	Optical lens	Alight optical lens with light beam and slit lamp oculars	Slit lamp oculars		
	3.7.5 Position slit lamp	Slit lamp	Move/turn joystick using right hand	Slit lamp oculars		
	3.7.6 Inspect right eye	Patient (right eye)		Slit lamp oculars		
3.8 Examine left eye with optical lens	3.8.1 Retrieve optical lens	Optical lens	Retrieve optical lens from slit lamp table with right hand			1.7
	3.8.2 Position slit lamp	Slit lamp	Move joystick with left hand	Slit lamp oculars		0.9
	3.8.3 Position arm	Doctor (right arm)	Raise arm and position right hand near patient face		Right arm extended (25.8s) Left hand repetitive fine motions	25.8
	3.8.4 Align optical lens	Optical lens	Alight optical lens with light beam and slit lamp oculars	Slit lamp oculars		
	3.8.5 Position slit lamp	Slit lamp	Move/turn joystick using left hand	Slit lamp oculars		
	3.8.6 Inspect left eye	Patient (left eye)		Slit lamp oculars		
3.9 Turn off light		Slit lamp table	Press switch using left hand			2.7

Appendix Table E.5: Task 3 (Examine Patient) breakdown with Key attributes for 50th percentile Male

Task 3 - Examine Patient		**Task Attributes**				
Subtask	**Element**	**Work object**	**Methods**	**Tools**	**Ergonomic concerns**	**Total Time (s)**
3.1 Position slit lamp table		Slit lamp table	Place both hands on the outsides of the slit lamp table			2.9
3.2 Turn on light		Slit lamp table	Flip embedded switch with left hand			0.9
3.3 Position chair		Chair	Move back rest using right hand. Slide chair forward using legs			1.1
3.4 Examine right eye	3.4.1 Position slit lamp	Slit lamp	Place left hand on the left dial		Left Arm extended (12.9s)	12.9
	3.4.2 Inspect right eye	Patient (right eye)		Slit lamp oculars		
	3.4.3 Adjust intensity	Slit lamp	Turn intensity dial - left hand			
	3.4.4 Position slit lamp	Slit lamp	Place left hand on the left dial			
	3.4.5 Inspect right eye	Patient (right eye)		Slit lamp oculars		

	3.5.1 Position slit lamp	Slit lamp	Place left hand on the left dial			
	3.5.2 Inspect left eye	Patient (left eye)		Slit lamp oculars		
3.5 Examine left eye	3.5.3 Adjust intensity	Slit lamp	Turn intensity dial using left hand		Left Arm extended (7.6s)	7.6
	3.6.1 Retrieve optical lens	Optical lens	Retrieve optical lens from slit lamp table with left hand			4
	3.6.2 Position slit lamp	Slit lamp	Move joystick with right hand	Slit lamp oculars		1.3
	3.6.3 Position arm	Doctor (left arm)	Raise arm and position left hand near patient face			
	3.6.4 Align optical lens	Optical lens	Alight optical lens with light beam and slit lamp oculars	Slit lamp oculars		
	3.6.5 Position slit lamp	Slit lamp	Move/turn joystick using right hand	Slit lamp oculars	Left arm extended (13.9)	
	3.6.6 Inspect right eye	Patient (right eye)		Slit lamp oculars		
3.6 Examine right eye with optical lens	3.6.7 Adjust intensity	Slit lamp	Turn intensity dial using left hand		Right hand repetitive fine motions	13.9
	3.7.1 Retrieve optical lens	Optical lens	Retrieve optical lens from slit lamp table with right hand			1.7
	3.7.2 Position slit lamp	Slit lamp	Move joystick with left hand	Slit lamp oculars		1.9
	3.7.3 Position arm	Doctor (right arm)	Raise arm and position right hand near patient face			
	3.7.4 Align optical lens	Optical lens	Alight optical lens with light beam and slit lamp oculars	Slit lamp oculars	Right arm extended (21.9)	
	3.7.5 Position slit lamp	Slit lamp	Move/turn joystick using left hand	Slit lamp oculars		
3.7 Examine left eye with optical lens	3.7.6 Inspect left eye	Patient (left eye)		Slit lamp oculars	Left hand repetitive fine motions	21.9
3.8 Turn off light		Slit lamp table	Press switch using left hand			1.6

Following the classification of each element, biomechanical analysis was performed on the elements that raised ergonomic concerns - namely the elements that involved sustained arm extensions. A 3D analysis tool - 3DSSPP - was used to predict strength capabilities, endurance, and duty cycle were calculated using existing web tools and shown in Table E.6 (Chaffin, 2005).

Appendix Table E.6: ACGIH TLV Duty cycle recommendation for different body parts for each practitioner

Practitioner	**Body Part**	**% MVC**	**Endurance (s)**	**Max recommended Duty cycle (%)**	**Observed Duty Cycle (%)**

95th Percentile Female	L Elbow	11	1077.0	71.1	
	L Shoulder	51	25.0	4.4	50.6
	R Elbow	11	1077.0	71.1	
	R Shoulder	51	25.0	4.4	27.0
5th Percentile Female	L Elbow	4	1200.0	100.0	
	L Shoulder	17	191.0	48.5	29.0
	R Elbow	4	1200.0	100.0	
	R Shoulder	17	191.0	48.5	21.5
50th Percentile Male	L Elbow	5	1200.0	100.0	
	L Shoulder	23	107.0	31.2	27.9
	R Elbow	5	1200.0	100	
	R Shoulder	23	107.0	31.2	22.8

Discussion

Several key points arose following the HTA analysis of the slit lamp exam. During the Examine Patient Task, the overall tasks that needed to be completed were to examine each eye of the patient first using the microscope, then using a lens. However, each practitioner had their own preference of ordering of sub-tasks, leading to differences in the duration of sustained postures. It should also be noted that despite the differences in sub-task preferences between the practitioners, it was common for their non-dominant hand to be held at a sustained posture longer than their dominant hand. It may be due to the fact that the dominant hand is better at the fine motor control task of aligning and positioning the slit lamp.

It was observed that each practitioner had sustained durations of repetitive hand motion of the dominant (right) hand during many of the “Examine eye” elements, however, fatigue analysis was not performed. Due to the sustained extension of their non-dominant (left) arm, the 95th percentile female exceeded the recommended duty cycle for their left and right shoulder, while the 50th percentile male also approached the max recommended duty cycle for his left shoulder. This current study only focuses on sustained postures of the upper limb, when additional variables (such as neck and back angles) are considered, the 3D analysis tool will be relied on more heavily. In addition, with progressing health concerns due to COVID-19, many slit-lamps are now equipped with a clear plastic shield. It is unclear how this shield impacts the ergonomics of the procedure, but it warrants further attention.

It should be noted that this pilot study contained a very small sample size with video recordings being taken from a non-stationary point of view of informal exam examples. Even with the limitations, it is clear that the slit lamp exam requires long periods of sustained posture that pose fatigue risks and is a job that can be improved potentially with something as simple as a padded armrest. Further investigations into interventions are still needed. This study also demonstrates the power of having a well-defined taxonomy and the ability to combine HTA with temporal and spatial information to derive ergonomic risks.

References

Armstrong, T., Yu, D., Frischknecht, A., Minter, R., Andreatta, P., & Kasten, S. (2012). Standardization of surgical procedures for identifying best practices and training. Work, 41(Supplement 1), 4673-4679.

Chaffin, D. B. (2005). 3D SSPP (Static Strength Prediction Program), version 5.04. Ann Arbor (MI): University of Michigan.

Chee, Y. E., Newman, L. R., Loewenstein, J. I., & Kloek, C. E. (2015). Improving the teaching skills of residents in a surgical training program: Results of the pilot year of a curricular initiative in an ophthalmology residency program. *Journal of surgical education*, *72*(5), 890-897.

Dhimitri, K. C., McGwin Jr, G., McNeal, S. F., Lee, P., Morse, P. A., Patterson, M., ... & Marx, J. L. (2005). Symptoms of musculoskeletal disorders in ophthalmologists. *American journal of ophthalmology*, *139*(1), 179-181.

Fethke, N. B., Schall Jr, M. C., Determan, E. M., & Kitzmann, A. S. (2015). Neck and shoulder muscle activity among ophthalmologists during routine clinical examinations. *International Journal of Industrial Ergonomics*, *49*, 53-59.

Honavar, S. G. (2017). Head up, heels down, posture perfect: Ergonomics for an ophthalmologist. *Indian journal of ophthalmology*, *65*(8), 647.

Lorch, A. C., & Kloek, C. E. (2017). An evidence-based approach to surgical teaching in ophthalmology. *Survey of Ophthalmology*, *62*(3), 371-377.

MacKenzie, L., Ibbotson, J. A., Cao, C. G. L., & Lomax, A. J. (2001). Hierarchical decomposition of laparoscopic surgery: a human factors approach to investigating the operating room environment. *Minimally Invasive Therapy & Allied Technologies*, *10*(3), 121-127.

Marx, J. L. (2012). Ergonomics: back to the future. *Ophthalmology*, *119*(2), 211-212.

Sarker, S. K., Chang, A., Albrani, T., & Vincent, C. (2008). Constructing hierarchical task analysis in surgery. *Surgical endoscopy*, *22*(1), 107-111.

Stanton, N. A. (2006). Hierarchical task analysis: Developments, applications, and extensions. *Applied ergonomics*, *37*(1), 55-79.

Yu, D., Kasten, S. J., & Armstrong, T. J. (2010, September). Development of a hierarchical taxonomy for standardization of microvascular surgery. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* (Vol. 54, No. 19, pp. 1595-1599). Sage CA: Los Angeles, CA: SAGE Publications.

APPENDIX F

Applications of MBWA with Emerging Methods

Introduction

A case study was performed examining the application of the MBWA framework integrates evolving technologies and methodologies to demonstrate model flexibility and broader applications. This case study applied the various components of the Model-Base Work Assessment framework on existing video work tasks with the goal of incorporating evolving techniques used for ergonomic exposure assessment - namely computer vision.

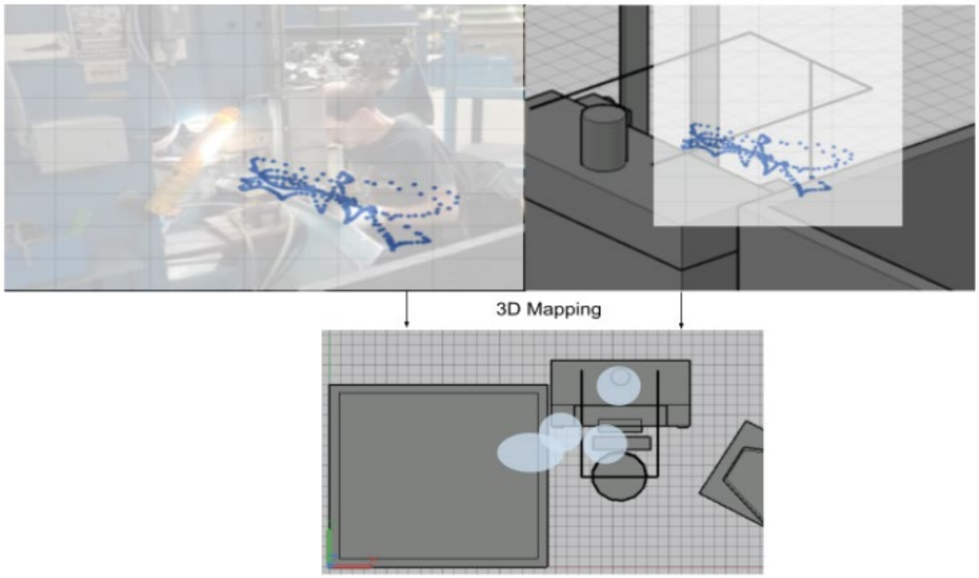
Computer vision has been gaining traction for ergonomic assessments in recent years with applications ranging from posture prediction (Green et al., 2019), hand motion maneuver prediction (Azari et al., 2019), and microscopic movement patterns (Li et al., 2019). The main benefit of using computer vision in job analysis is that it is less subjective than traditional time study approaches. However, key limitations of these previous works are that they do not provide relationships of computer vision results to key work parameters. This reduces the generalizability of computer vision when looking at biomechanical load patterns. By incorporating the use of computer vision into Model-based Work Analysis, it is possible to accurately determine kinematic patterns in the context of a 3D spatial model It also allows for adding in the time domain and work cycles through the use of PTS to predict and evaluate ergonomic exposures and risk.

Methods

The approach to this case study utilizes the Spatial, Temporal, Ergonomic, and Force model developed in the previous studies and apply the Model-Based work assessment framework in a real-world setting. Ergonomic exposure assessments will be performed using the Model-based approach as well as using time study approach; those outcomes will then be supplemented with computer vision analysis. The computer vision tool will be used to track link movements, with initial analysis focused on the hand and wrist. The computer vision will contribute in creating a kinematic profile of movement patterns of the worker that can predict ergonomic exposure and various risks when used together with the CAD and PTS portion of the MBWA framework.

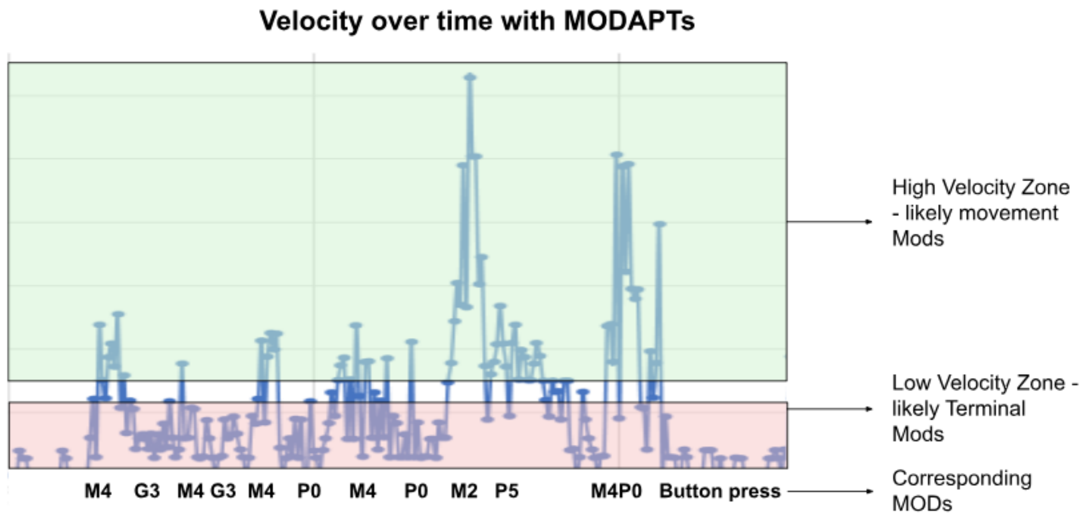
Results

The MBWA approach should allow us to identify potential ergonomic risks and issues in the work tasks that are re-created in the lab. Using the framework, it will be possible to also simulate variations of movement patterns on the job. In addition, by adding in the kinematic profiles generated using computer vision, this study should demonstrate the generalizability of this framework to be used with new and evolving technologies and methodologies. A pilot video of a worker performing a welding task was analyzed using computer vision and a kinematic profile created for the left hand using openpose (Cao et al., 2019). The frame by frame location as detected by computer vision is overlayed over an image of the worker as shown in Figure F.1.



Appendix Figure F.1: (Top left) Frame by frame location of left hand overlaid over an image of worker performing task. (Top right): Left hand location overlaid over CAD model; (bottom) 3D transformation to determine movement hot spots

Using the computer vision data, it would be possible to perform a transformation of the location data to map for “hot spots” for the hand (shown in Figure 9c), giving insight into location and movement patterns. Following, velocity over time was also generated. The relatively high velocity portions of movement would correspond to movement Mods and the relatively idle portions would represent a terminal element (Get or Put). An initial categorization of MODAPTS based on velocity is shown in Figure F.2.



Appendix Figure F.2: Velocity determined using computer vision (openpose) for the left hand over a short video with MODAPTS categorization

Application to future work

While the pilot data involving computer vision is limited, when used in conjunction with wearable sensing and traditional motion capture methodologies, a more robust kinematic profile can be created in the laboratory. Combining the kinematic profiles with the MBWA framework creates a structured approach for proactive work analysis. The results of this study should demonstrate the functionality of applying the framework and creating quantifiable metrics of improvements using emerging tools as well as the broader applicability of this approach.

References

Azari, D. P., Hu, Y. H., Miller, B. L., Le, B. V., & Radwin, R. G. (2019). Using surgeon hand motions to predict surgical maneuvers. Human factors, 61(8), 1326-1339.

Cao, Z., Hidalgo, G., Simon, T., Wei, S. E., & Sheikh, Y. (2019). OpenPose: realtime multi-person 2D pose estimation using Part Affinity Fields. IEEE transactions on pattern analysis and machine intelligence, 43(1), 172-186.

Greene, R. L., Hu, Y. H., Difranco, N., Wang, X., Lu, M. L., Bao, S., ... & Radwin, R. G. (2019). Predicting sagittal plane lifting postures from image bounding box dimensions. Human factors, 61(1), 64-77.

Li, Y., Wolf, M., Kulkarni, A., Bell, J., Chang, J., Nimunkar, A., & Radwin, R. G. (2019, November). Quantification of In Situ Tremor in Microscopic Surgery. In Proceedings of the Human Factors and Ergonomics Society Annual Meeting (Vol. 63, No. 1, pp. 1067-1068). Sage CA: Los Angeles, CA: SAGE Publications.