A. COVER PAGE

Project Title: The Low Back Cumulative Trauma Index: A Fatigue-Failure Based Risk Assessment Tool	
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Change of Contact PD/PI: NA	
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Human Subjects: NA	**Vertebrate Animals:** NA
hESC: No	**Inventions/Patents:** No

B. ACCOMPLISHMENTS

B.1 WHAT ARE THE MAJOR GOALS OF THE PROJECT?

The goal of the research performed on this grant was twofold: The first aim was to evaluate the accuracy of estimated 3D L5/S1 moments occurring during manual lifting tasks using a wearable inertial motion capture (IMC) system. A total of 36 subjects performed tasks consisting of lifting and lowering one of three loads (10, 20, and 30 lbs.) to one of three different heights (60, 100, and 140 cm) and three different asymmetry angles (0°, 30°, and 60°). The root means square errors (RMSE) and absolute peak errors (Ranges) between models were compared as a measure of system performance. A Randomized Block Partially Confounded design was used, comparing the means and the absolute peaks (ranges) of the estimated moments between the IMC system and the OMC reference system. Averaged over subject and trials, L5/S1 moment RMS errors remained around 15 to 20 Nm, while the peak moment differences observed were 10 to 15% between the OMC and IMC-based models for both lifting and lowering tasks. In conclusion, a close correspondence was found between the IMC-based and laboratory-based backload estimates.
The second aim was to perform a field study which aimed to develop a systematic data processing framework that uses fatigue failure theory as the core method in estimating cumulative exposure with the ability to use continuous low-back loading information captured by Inertial Measurement Units (IMU) technology. Eight workers from an automotive manufacturing facility volunteered as participants, while they performed their regular work; L5/S1 moments were calculated using a top-down approach from a biomechanical model based on IMUs. A total of 108 trials were evaluated. Each trial corresponded to one complete working cycle of a specific car model at a particular workstation. Low back injury recorded data provided by the company and self-reported injuries from surveys completed by the workers were compared against the model predicted risk using chi-square tests. As far as the authors know, this is the first attempt at estimating continuously accruing cumulative damage using a fatigue failure-based approach. The initial results are promising, as the estimates of risk from the cumulative damage total showed a significant association with self-reported low back pain ($\chi 2$ (df = 1, n = 108) = 5.01, p-value = 0.024), and with the low back injuries reported by the manufacturer ($\chi 2$ (df = 1, n = 108) = 12.65, p-value < 0.001). The results of this study provide additional evidence that musculoskeletal disorders are the results of a fatigue failure process and provides the first (to our knowledge) method of assessing cumulative damage using continuous loading data.

B.1.a Have the major goals changed since the initial competing award or previous report?

No

B.2 WHAT WAS ACCOMPLISHED UNDER THESE GOALS?

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B.3 COMPETITIVE REVISIONS/ADMINISTRATIVE SUPPLEMENTS

For this reporting period, is there one or more Revision/Supplement associated with this award for which reporting is required?

No

B.4 WHAT OPPORTUNITIES FOR TRAINING AND PROFESSIONAL DEVELOPMENT HAS THE PROJECT PROVIDED?

NOTHING TO REPORT

B.5 HOW HAVE THE RESULTS BEEN DISSEMINATED TO COMMUNITIES OF INTEREST?

Conference Presentations

• Nail-Ulloa, I., Gallagher, S., Huangfu, R., Bani-Hani, D., & Pool, N. (2021, September). Validation of a Wireless Sensor System for the Estimation of Cumulative Lumbar Loads in Occupational Settings (Pilot Results). In Proceedings of the Human Factors and Ergonomics Society Annual Meeting (Vol. 65, No. 1, pp. 489-494). Sage CA: Los Angeles, CA: SAGE Publications.
Symposia
• Nail-Ulloa, I., Gallagher, S., Huangfu, R., Bani-Hani, D., & Pool, N. (2021, October). Validation of a Wireless Sensor System for the Estimation of Cumulative Lumbar Loads in Occupational Settings (Pilot Results), Samuel Ginn College of Engineering, Auburn University.
• Nail-Ulloa, I., Gallagher, S., Huangfu, R., Bani-Hani, D., & Pool, N. (2021, March). Validation of a Wireless Sensor System for the Estimation of Cumulative Lumbar Loads in Occupational Settings (Biomechanical Modeling). Southeast Regional Research Symposium, Deep South Center for Occupational Health and Safety ERC, Central Appalachian Regional ERC, Sunshine ERC, North Carolina Occupational Safety and Health ERC, Southeastern Coastal Center for Agricultural Health and Safety, and Southeast Center for Agricultural Health and Injury Prevention. (Remote Symposium).
Webinars
• Fatigue failure theory and its relationship with musculoskeletal disorders. Webinar. Chilean Society of Ergonomics, Santiago, Chile. July 13th, 2021.
• An Introduction to ergonomic risk factors, Webinar. Institute of Management and Industry, Universidad Austral de Chile, Puerto Montt, Chile. October 9th, 2020.
Dissertation/Thesis
• Doctoral Thesis: Validation of a wireless sensor system for the estimation of cumulative lumbar loads in occupational settings. Ph.D. Candidate Ivan Nail Ulloa, Industrial and Systems Engineering, Auburn University. Expected graduation: Fall 2022.

B.6 WHAT DO YOU PLAN TO DO DURING THE NEXT REPORTING PERIOD TO ACCOMPLISH THE GOALS?

Not Applicable

The Low Back Cumulative Trauma Index: A Fatigue-Failure Based Risk Assessment Tool

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Final Report (Completed August 31, 2022)

Contents

List of terms and abbreviations

ASTM American Society for Testing and Materials

ANOVA Analysis of Variance

BU Bottom-Up

DUET Distal Upper Extremity Tool

FP Force Plates

IMC Inertial Motion Capture

IMU Inertial Measurement Unit

LIFFT Lifting Fatigue Failure Tool

N-Pose Neutral Posture

NIOSH National Institute for Occupational Safety and Health

MSD Musculoskeletal Disorder

OMC Optical Motion Capture

OSHA Occupational Safety and Health Administration

REBA Rapid Entire Body Assessment

RMSE Root Mean Square Error

RULA Rapid Upper Limb Assessment

S_a Alternating Stress

S_m Mean Stress

S_{Nf} Estimated value of the stress at failure for exactly Nf cycles as determined by an S-N diagram

S_u Ultimate Stress

TD Top-Down

UTS Ultimate Tensile Strength

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Abstract

The goal of the research performed on this grant was twofold: The first aim was to evaluate the accuracy of estimated 3D L5/S1 moments occurring during manual lifting tasks using a wearable inertial motion capture (IMC) system. A total of 36 subjects performed tasks consisting of lifting and lowering one of three loads (10, 20, and 30 lbs.) to one of three different heights (60, 100, and 140 cm) and three different asymmetry angles (0°, 30°, and 60°). The root means square errors (RMSE) and absolute peak errors (Ranges) between models were compared as a measure of system performance. A Randomized Block Partially Confounded design was used, comparing the means and the absolute peaks (ranges) of the estimated moments between the IMC system and the OMC reference system. Averaged over subject and trials, L5/S1 moment RMS errors remained around 15 to 20 Nm, while the peak moment differences

observed were 10 to 15% between the OMC and IMC-based models for both lifting and lowering tasks. In conclusion, a close correspondence was found between the IMC-based and laboratory-based backload estimates.

The second aim was to perform a field study which aimed to develop a systematic data processing framework that uses fatigue failure theory as the core method in estimating cumulative exposure with the ability to use continuous low-back loading information captured by Inertial Measurement Units (IMU) technology. Eight workers from an automotive manufacturing facility volunteered as participants, while they performed their regular work; L5/S1 moments were calculated using a top-down approach from a biomechanical model based on IMUs. A total of 108 trials were evaluated. Each trial corresponded to one complete working cycle of a specific car model at a particular workstation. Low back injury recorded data provided by the company and self-reported injuries from surveys completed by the workers were compared against the model predicted risk using chi-square tests. As far as the authors know, this is the first attempt at estimating continuously accruing cumulative damage using a fatigue failure-based approach. The initial results are promising, as the estimates of risk from the cumulative damage total showed a significant association with self-reported low back pain ($\chi2$ (df = 1, n = 108) = 5.01, p-value = 0.024), and with the low back injuries reported by the manufacturer ($\chi2$ (df = 1, n = 108) = 12.65, p-value < 0.001). The results of this study provide additional evidence that musculoskeletal disorders are the results of a fatigue failure process and provides the first (to our knowledge) method of assessing cumulative damage using continuous loading data.

Section 1 of Final Progress report

Significant or Key Findings.

The first aim was evaluate the accuracy of estimated 3D L5/S1 moments occurring during manual lifting tasks using a wearable inertial motion capture (IMC) system The Averaged over subject and trials, L5/S1 moment RMS errors remained around 15 to 20 Nm, while the peak moment differences observed were 10 to 15% between the gold standard optical motion capture (OMC) and IMC-based models for both lifting and lowering tasks. A close correspondence was found between the IMC-based and laboratory-based back load estimates.

The second aim was to perform a field study in which continuous data on low back loading was collected and established fatigue failure methods of evaluating cumulative damage development for continuous data (i.e., Rainflow Analysis) to estimate the cumulative exposure with the ability to use continuous low-back loading information captured by Inertial Measurement Units (IMU) technology. Eight workers from an automotive manufacturing facility volunteered as participants, while they performed their regular work; L5/S1 moments were calculated using a top-down approach from a biomechanical model based on IMUs. A total of 108 trials were evaluated. Each trial corresponded to one complete working cycle of a specific car model at a particular workstation. Low back injury recorded data provided by the company and self-reported injuries from surveys completed by the workers were compared against the model predicted risk using chi-square tests. Though the data collection was affected by the Covid pandemic, the data indicated that the method of cumulative damage estimation mentioned above was significantly associated with both low back injuries and reports of low back pain.

Translation of Findings.

Results of the research on this grant provide additional evidence that musculoskeletal disorders (MSDs) may the result of a fatigue failure process in musculoskeletal tissues. If so, there are numerous techniques and methods that may be able to be used to improve the risk assessment of MSDs. As shown here, data collected on the continuous load experienced by the lumbar spine could be analyzed and the cumulative damage associated with the complex and highly variable loading could be estimated using rainflow analysis techniques. Estimates of cumulative damage using this fatigue failure technique were also found to be associated with historical low back injuries and reported low back pain on surveys from workers of the cooperating manufacturer.

Translation has been a bit impeded due to the pandemic and other factors; however, research on the laboratory study have been presented at the Human Factors and Ergonomics Society International meeting in 2021, and a journal article is being submitted to the journal *Human Factors* currently. Results of the second study are still quite fresh, however, these are being put together for a submission of the journal *Applied Ergonomics*.

Research Outcomes/Impact.

The results of this research may lead to several improvements in occupational health and safety. One of the main findings is that fatigue failure methods can be used to evaluate the risk of musculoskeletal disorder development. One benefit to this is that a number of techniques and methods are available to help assess the cumulative loading experienced by workers that may lead to MSD development. It has been believed by many in the field that MSDs are the result of the cumulative load experienced by workers; however, the methods developed for cumulative damage assessment have been based on rather scant evidence. On the other hand, fatigue failure theory has established, validated methods of assessing the effect of cumulative loading on materials, even for highly variable loading conditions (spectrum loading). This spectrum loading is commonly experienced by human beings (including in occupational settings), and having validated methods of assessing the cumulative effect of spectrum loading is believed to be of significant value in terms of MSD risk assessment. Results of this study suggest that these methods are associated with low back pain outcomes (historical data on back injuries and current low back pain survey data). Currently many methods of assessing continuous loading are being developed (using video and inertial measurement devices). The techniques evaluated here may be able to assess the cumulative load associated with such continuous loading data measurement systems.

1. Scientific Report - Study 1: Validation of a wireless sensor system for the estimation of cumulative lumbar loads in occupational settings

ABSTRACT:

The aim of this study was to evaluate the accuracy of estimated 3D L5/S1 moments occurring during manual lifting tasks using a wearable inertial motion capture (IMC) system. Reference L5/S1 moments were calculated using inverse dynamics bottom-up and top-down laboratory models based on the data from a measurement system comprising optical motion capture (OMC) and force plates. A total of 36 subjects performed tasks consisting of lifting and lowering one of three loads (10, 20, and 30 lbs.) to one of three different heights (60, 100, and 140 cm) and three different asymmetry angles (0°, 30°, and 60°). The root means square errors (RMSE) and absolute peak errors (Ranges) between models were compared as a measure of system performance. A Randomized Block Partially Confounded (RBPF) design was used, comparing the means and the absolute peaks (ranges) of the estimated moments between the IMC system and the OMC reference system. Averaged over subject and trials, L5/S1 moment RMS errors remained around 15 to 20 Nm, while the peak moment differences observed were 10 to 15% between the OMC and IMC-based models for both lifting and lowering tasks. In conclusion, a close correspondence was found between the IMC-based and laboratory-based backload estimates.

1.1 Introduction

Mechanical loading of the spine has been identified as an important risk factor for low-back pain (Coenen et al., 2013; da Costa & Vieira, 2009) and still is a significant economic burden (Vos et al., 2012). Laboratory studies have investigated the effects of ergonomic interventions on spinal loading by estimating L5/S1 moments through inverse dynamic analysis (Kingma et al., 1996) ,employing laboratory-based instrumentation such as optical motion capture (OMC) systems, force plates (FPs), and boxes instrumented with force sensors. The effects of interventions in constrained laboratory conditions might not reflect results in practice (Faber et al., 2011). Therefore, it is recommended to perform these intervention studies in real-world environments (Lötters & Burdof, 2002); however, utilizing the above-mentioned laboratory-based instrumentation is often not feasible or practical. To face this limitation, some wearable measurement systems have been developed for ambulatory assessment of backloading (Freitag et al., 2007; Marras et al., 2010). Nevertheless, these systems are bulky, which could be problematic in occupational settings and highly dynamic conditions. Another alternative is provided by inertial motion capture (IMC) systems, consisting of small inertial/magnetic measurement units (IMUs) measuring body segment orientations. IMC systems have shown good validity for assessing L5/S1 moments during trunk bending (Faber et al., 2016). It has also been tested that when combining IMUs sensors and force-sensing shoes, lumbar moments could be estimated within 10 to 20% of peak extension moments for manual lifting tasks (Faber et al., 2020). However, using force-sensing shoes, which could be bulky for a real work environment, invites us to think about an approach using just the IMU-based system. Lastly, the impact of different loads, heights, and asymmetry keeps the question open about how the system could deal with these factors.

The current study investigates if 3D L5/S1 moments can be accurately assessed by using an ambulatory measurement system consisting of an IMC system, evaluating the impact of three main factors, the weight of the load, asymmetry, and height associated with the lifting and lowering tasks. The comparisons were made against bottom-up and top-down laboratory models consisting of OMC and FPs.

1.2 Methods

1.2.1 Participants

A gender-balanced sample of 36 subjects (ages between l9 to 55 years old; mean height = 173.54 cm ± 7.5 SD; mean body mass = 72.78 kg ± 12.1 kg SD) was recruited. Participants were from the Auburn University student body and the local Auburn/Opelika community. Inclusion criteria included 1) no history of physician-diagnosed MSD, injury, or surgery in the low back, 2) absence of low back pain during the previous six months, and 3) no history of a physician-diagnosed neurodegenerative disorder that may affect movement (e.g., Parkinson's disease, multiple sclerosis, among others). Details about subjects' anthropometry are shown in Table 1.

	Body weight (kg)	Body height (cm)	Shoe length (cm)	Ankle height (cm)	Ankle width (cm)	Knee height (cm)	Knee width (cm)	Elbow width (cm)	Shoulder width (cm)	Shoulder height (cm)	Hip height (cm)	Hip width (cm)	Arm span (cm)
Mean	72.78	173.54	25.06	8.72	7.92	46.96	10.84	8.42	34.28	142.05	90.88	24.53	172.09
SD	12.1	7.5	1.3	10.0	6.8	9.8	6.5	10.1	3.3	6.8	8.9	2.0	9.1

Table 1. Summary of subjects' anthropometry.

1.2.2 Subject Preparation and Data Collection

Anthropometric measurements were taken, including height, weight, and the lengths and circumferences of several major body links, following established guidelines (Pheasant & Haslegrave, 2018). Subjects were fitted with 17 IMU sensors (MVN Awinda, Xsens Technologies B.V., Enschede, the Netherlands). Each IMU is a small wireless, battery-powered unit that measures and stores acceleration, angular velocity, and magnetic field information. The sensors were secured using a combination of elastic neoprene straps and/or hypoallergenic athletic tape. In addition to the IMUs, the participants also had small, reflective optical motion capture markers affixed at particular reference points on their bodies. OMC was used as a "gold-standard" reference for body segment position. The OMC system recorded the reflective marker trajectories with sixteen cameras (Optitrack Prime 13, Natural Point, Inc.), using a full-body protocol. For this experiment, a total of 50 reflective markers were used. A full body Plug-In Gait 39-marker set (Vicon®, 2002) was selected to define the primary reflective marker locations; 11 more markers were added to the 39 basic marker set to keep track of some segments that could lose track of reflective markers due to the nature of the exertion subjects were required to complete. The additional 11 markers were added to the inside of the knees, elbows, and ankles, top of the feet, the left and right sides of the pelvis, and the sternum (Figure 1). The anthropometric data was used to build a rigid link biomechanical model using the information collected from the IMU sensors. The model was compared against the OMC model based on the data collected from the reflective markers.

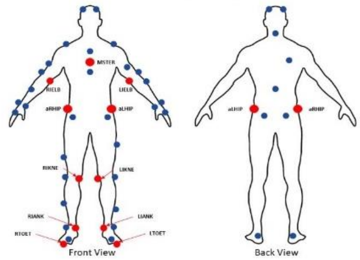

Fig 1. Adapted Plug-In Gait marker set

1.2.3 Systems Calibration

The OMC system was calibrated prior to each data collection session, defining the capture volume and the global coordinate system's orientation and origin. Before the task completion, subjects were required to follow calibrations protocols for both the OMC system and the IMC system. Segment calibration on the IMC system is necessary to align the motion trackers to the subject segments (Xsens®, 2021). The procedure consists of the subject holding a neutral posture for a few seconds (N-pose), then walking straight forward and back to the point where they started. Segment calibration on the OMC system (NaturalPoint®, 2018) requires the subject to hold an "A" pose (Figure 1) to record a static trial; this static trial is assigned to the dynamic files corresponding to each subject for posterior biomechanical analysis.

1.2.4 Data Synchronization and Processing

Motion analysis data was captured using the OMC and IMC systems simultaneously. OMC data was sampled at 120Hz, while IMC data was sampled at 60Hz. Force plates, OMC, and IMC data were measured synchronously using Motive™ software from Optitrack (Natural Point Inc, Corvallis, OR, USA) as the master system. OMC signals were down-sampled to 60Hz offline. Forces and kinematics were bi-directionally low-pass filtered with a second-order Butterworth filter at 6Hz for the OMC system (Karatsidis et al., 2016) and 5 Hz for the IMC system (Faber et al., 2020). The gaps in the OMC markers' trajectory were filled using cubic interpolation methods (Xu et al., 2010) in the Motive™ software.

1.2.5 Experimental Procedure

The 36 participants were instructed to perform different manual material handling tasks, where kinematic and kinetic data were collected. Each subject performed three trials with a 2-minute rest period between each other. Subjects were instructed to lift boxes (similar to a standard milk crate) with handles consisting of three loads 10 lbs. (4.54 kg), 20 lbs. (9.07 kg), and 30 lbs. (13.61 kg) both symmetrically and asymmetrically (i.e., 0°, 30° and 60° degrees from sagittal to the left) within three different heights of the shelf (60 cm, 100 cm, and 140 cm). The experimental trials lasted between 15 to 60 seconds, depending on the subject's lifting and lowering speed. Each subject completed three different combinations, using a lifting technique of their preference. The tested combinations were labeled using the following terminology: LXX (XX = Load of 10, 20, or 30 lbs.), AYY (YY = Angle of 00-, 30- or 60-degrees asymmetry), and HZZ (ZZ = Height of 60, 100, or 140 cm.). For example, L20_A30_H140 would represent a 20-pound load, picked up from a sagittal angle of 30° and lifted to a height of 140 centimeters. Loads and heights were randomized within levels of angle for a total of 27 different combinations (every combination was performed four times, that means 108 trials). The combinations for the settings are shown in Table 2.

1.2.6 Biomechanical Modelling

Biomechanical models employing both bottom-up and top-down approaches were used to analyze the data. A body model consisting of 15 segments was developed in Visual3D software (C-Motion, Rockville, MD) using the OMC data. The position estimate for L5-S1 was defined according to guidelines (Dumas et al., 2007; Reed et al., 1999) using proportions of the anterior superior iliac spine (ASIS) distance. The biomechanical model used for the IMC system was the one developed by Visual3D to use within their software (C-Motion®, 2020). For the Top-Down models, the external load was assigned to both hands equally when the subject was lifting/lowering the load (by using the changes in magnitude observed in the FP). Total moments were calculated for the analyses. The total moment is the vector summation of each plane's L5/S1 moments (X, Y, Z). The peak moments were identified based on the OMC-BU estimates.

1.2.7 Data Analysis

As a measure of system performance, randomized block partially confounded designs 3^3 (RBPF) with blocks of size three were calculated comparing the ranges and the RMSE of the estimated moments.

	Height		
Load	**60 cm**	**100 cm**	**140 cm**
10 lbs	0°	0°	0°
	30°	30°	30°
	60°	60°	60°
20 lbs	0°	0°	0°
	30°	30°	30°
	60°	60°	60°
30 lbs	0°	0°	0°
	30°	30°	30°
	60°	60°	60°

Table 2. Different combinations of load, height, and angle.

Confounded factorial designs are particularly appropriate if an interaction is expected to be negligible. The interactions can be confounded with groups, thereby achieving a reduction in block size without sacrificing power in evaluating the treatments (Kirk, 2013) . Due to the nature of the experimental design technique utilized, groups (four groups of nine subjects each) and the main effects (Load, Angle, Height, and its possible interactions) were analyzed in order to find potentially significant differences. A significance level of 0.05 was used for all tests. Pairwise comparisons were performed using Tukey's test for the analysis of the RMSE and ranges for the main effects and interactions found as significant. Statistical tests were conducted in Minitab® (version 19.2020.1, LLC, USA).

1.3 Results

Figure 2 and Figure 3 present typical results of moment estimates associated with the lifting and lowering trials, showing the Bottom-Up Optical Motion Capture-based model (OMC-BU), the Top-Down Optical Motion Capture-based model (OMC – TD), and the Top-Down Inertial Motion Capture-based model (IMC-TD). Both figures from the lifting and lowering show two different peaks, with the higher one being, in general, picking up or putting down the load from and to the floor level, and the other one is putting on or removing the load from the shelf. Measures of central tendency are shown in Tables 3 and 4.

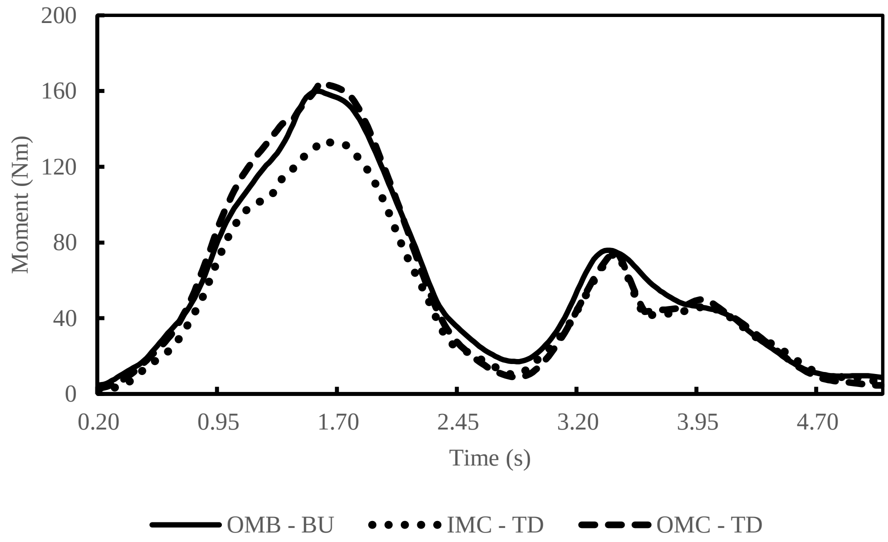

Fig 2. L5/S1 Moment during one of the lifting trials

1.3.1 Lifting Task

The results for the RBPF design for the ranges were separated depending on the analyzed system and approach used (Table 5). When analyzing the ranges for the OMC-BU calculations, the load ($p < 0.001$) and angle ($p = 0.02$) were identified as significant main effects, no significant interactions were found. The results for the IMC-TD calculations the load ($p < 0.001$) was found as a significant factor. Again, the load ($p < 0.001$) was the only factor found as significant for the OMC-TD calculations. Groups ($p < 0.001$) was found as a significant factor for all systems.

For the RMSE analysis using the RBPF design (Table 6), the OMCBU-OMCTD results showed that the load ($p < 0.001$) was a significant factor. When comparing the OMCBU-IMCTD, groups ($p < 0.1$) and Load ($p < 0.001$) were significant, but we also observed the presence of the significant interaction Load x Height ($p = 0.003$). Tukey's test calculations suggested that the pair L30_H060 & L30_H100 were significantly different ($T = 4.82 > 4.602$). The comparison of the OMC-TD and IMC-TD showed that groups ($p < 0.001$), Load ($p = 0.014$) and Height ($p = 0.001$) were significant. The interaction between Load x Height was also observed as significant ($p = 0.01$). Tukey's test calculations suggested that the pair L20_H060 – L20_H100 was significantly different ($T = 7.26 > 5.953$). One of the interactions of Load x Height is shown in Figure 4.

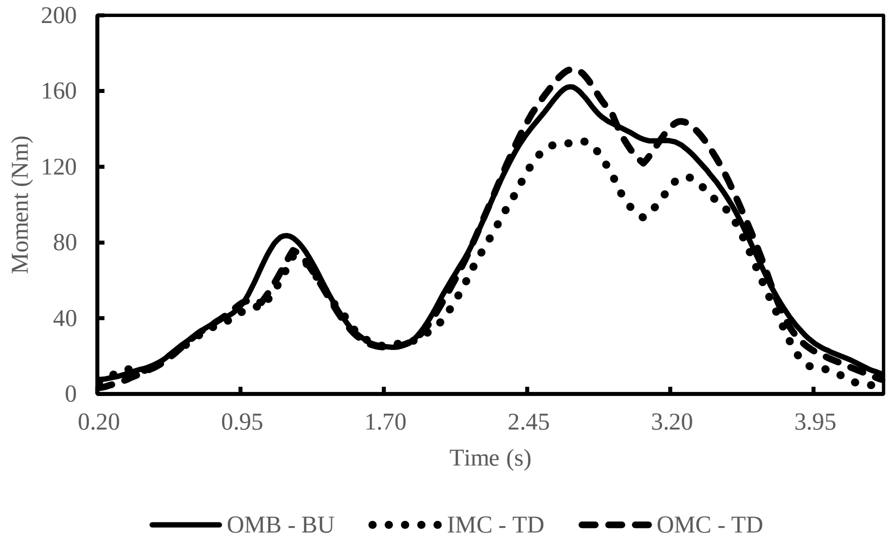

Fig 3. L5/S1 Moment during one of the lowering trials

1.3.2 Lowering Task

For the Ranges, as Table 5 shows, the load ($p < 0.001$) was identified as significant for the OMC-BU calculations. In the results for the IMC-TD calculations, as with the lifting trial, the load ($p < 0.001$) was found as a significant factor. Again, the load ($p < 0.001$) was the only factor found as significant for the OMC-TD calculations. Groups ($p < 0.001$) was found as a significant factor for all systems.

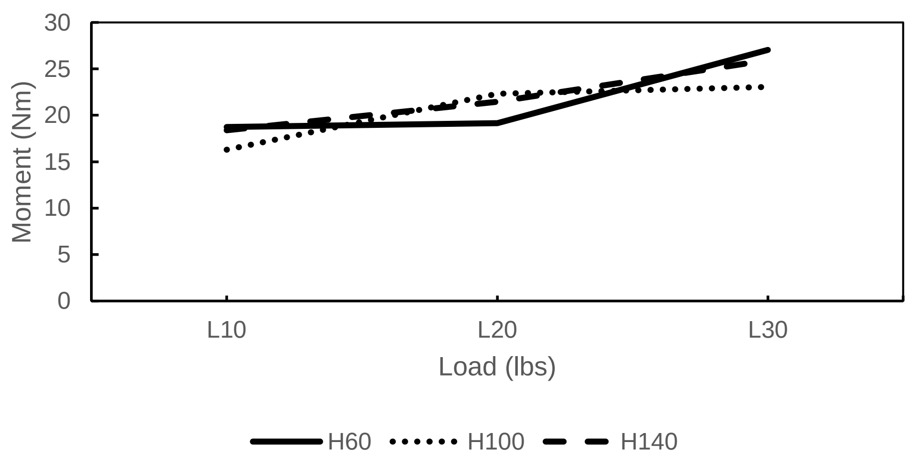

Fig 5. Load x Height Interaction for the OMC-BU and IMC-TD RMSE for the lowering portion of the trial

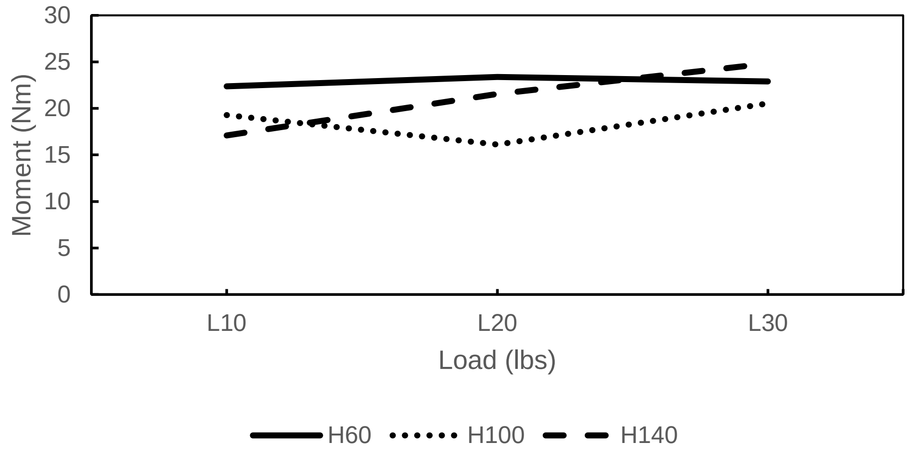

Fig 4. Load x Height Interaction for the OMC-TD and IMC-TD RMSE for the lifting portion of the trial

	Ranges (Nm)					
	Lifting			Lowering		
	OMC BU	IMC TD	OMC TD	OMC BU	IMC TD	OMC TD
Mean	197.59	171.63	208.59	188.47	166.24	200.57
Median	195.02	166.87	206.24	186.59	161.45	199.47
SD	45.09	42.5	44.3	41.1	39.74	40.93
Max	320.25	295.35	358.91	284.01	291.89	329.92
Min	110.91	97.66	121.12	96.55	98.14	120.45
IQR	69.38	63.85	56.47	62.11	58.65	53.05

Table 3. Measures of central tendency for the Ranges.

For the RMSE analysis using the RBPF design (Table 6), we started our comparison with the OMCBU-OMCTD; the results showed that the groups ($p < 0.025$) and load ($p < 0.001$) were significant factors. When comparing the OMCBU-IMCTD, groups ($p < 0.001$) and Load ($p < 0.001$) were significant, but we also observed the presence of the significant interaction Load x Height ($p = 0.032$) as for the lifting trial. Tukey's test calculation did not suggest any pair as significantly different. The comparison of the OMC-TD and IMC-TD showed that groups ($p < 0.001$) and height ($p = 0.003$) were significant. The interaction between Load x Height was also observed as significant ($p = 0.028$). Tukey's test calculations suggested that the pair L20_H060 & L20_H100 (as for the lifting trial) was significantly different ($T = 7.43 > 6.136$). One of the interaction plots of Load x Height is shown in Figure 5. Tables 3 and 4 show an overview of the results for the ranges and the RMSE for both lifting and lowering tasks.

	RMSE (Nm)					
	Lifting			Lowering		
	OMC BU - OMC-TD	OMC BU - IMU TD	OMC TD - IMC TD	OMC BU - OMC TD	OMC BU - IMU TD	OMC TD - IMC TD
Mean	16.03	19.07	20.9	16.95	21.38	21.34
Median	15.5	18.05	19.78	16.06	20.74	19.49
SD	6.4	5.94	8.56	6.79	7.24	8.96
Max	39.64	34.74	46.95	43.3	41.72	47.12
Min	4.92	8.2	7.35	4.22	6.18	6
IQR	7.86	7.96	11.99	7.36	9.54	11.97

Table 4. Measures of central tendency for the RMSE.

Factors	Ranges					
	Lifting			Lowering		
	OMC BU	IMC TD	OMC TD	OMC BU	IMC TD	OMC TD
Groups	***<0.001***	***<0.001***	***<0.001***	***<0.001***	***<0.001***	***<0.001***
A (LOAD)	***<0.001***	***<0.001***	***<0.001***	***<0.001***	***<0.001***	***<0.001***
B (ANGLE)	0.020	0.185	0.445	0.705	0.582	0.735
C (HEIGHT)	0.172	0.375	0.595	0.813	0.747	0.890
A*B	0.389	0.404	0.474	0.142	0.230	0.157
A*C	0.431	0.710	0.953	0.399	0.642	0.701
B*C	0.737	0.411	0.474	0.318	0.634	0.452
A*B*C	0.945	0.562	0.902	0.831	0.464	0.929

Table 5. Results (p-values) of the ANOVA analyses, testing the effects of the Loads (A), Angle (B), Height (C) and their interactions on the Ranges (Absolute Peaks) for the L5/S1 total moment. Significant effects ($p < 0.05$) are indicated in ***bold/italic***.

Factors	RMSE					
	Lifting			Lowering		
	OMC BU - OMC-TD	OMC BU - IMU TD	OMC TD - IMC TD	OMC BU - OMC TD	OMC BU - IMU TD	OMC TD - IMC TD
Groups	0.148	***<0.001***	***<0.001***	***0.025***	***<0.001***	***<0.001***
A (LOAD)	***<0.001***	***<0.001***	***0.014***	***<0.001***	***<0.001***	0.563
B (ANGLE)	0.472	0.448	0.500	0.233	0.457	0.733
C (HEIGHT)	0.340	0.072	***0.001***	0.239	0.462	***0.003***
A*B	0.290	0.613	0.305	0.717	0.620	0.225
A*C	0.986	***0.003***	***0.010***	0.474	***0.032***	***0.028***
B*C	0.424	0.575	0.848	0.424	0.246	0.490
A*B*C	0.840	0.390	0.812	0.562	0.939	0.934

Table 6. Results (p-values) of the ANOVA analyses, testing the effects of the Loads (A), Angle (B), Height (C) and their interactions on the RMSE of the L5/S1 total moment. Significant effects ($p < 0.05$) are indicated in ***bold/italic.***

1.4 Discussion

The present study evaluated the performance of the IMC system for the estimation of L5/S1 moments with different configurations of load, height, and angle of asymmetry. Outcomes of a state-of-the-art laboratory system, consisting of an OMC and FPs, bottom-up OMC model, were compared against a top-down IMC model. For internal validation of the OMC system, L5/S1 moments were also calculated using a top-down OMC model. For top-down estimates of L5/S1 moments, the weight of the load was divided between each hand equally.

The load was the most significant factor in almost all cases influencing the ranges and the RMSE; we did not find any solid statistical trend regarding the interactions observed for the RMSE; they were primarily for just one of the pairwise comparisons, we suspect this being related to subject variability. Hence, the influence of angles and height was not a significant factor overall in the tested scenarios. Averaged over subject and trials, L5/S1 moment RMS errors remained around 15 to 20 Nm. While the peak moment differences observed were 10 to 15% between the OMC and IMC-based models for lifting and lowering tasks. These results are in close correspondence with similar studies ((Faber et al., 2020; Koopman et al., 2018). Considering the obtained results, the approach of distributing the load between the subjects' hands seems to be promising with at least similar types of loads (symmetrical and evenly balanced); we recognize that in industry, tools have different shapes and weight distribution. Nevertheless, we find these results worth exploring when analysis needs to be simplified.

When comparing the moment estimates for the trials, a common situation was that the IMC system's estimates were lower than those obtained from the OMC-based models (Table 3 and 4). We have observed similar scenarios in the literature (Faber et al., 2016); we believe that these results come from how the segments are tracked and defined differently between systems. OMC-based models rely on real bony landmarks to determine segment lengths, which might be more accurate than the IMC-based model estimates, calculated using segment orientation and some key anthropometric characteristics from the subject (height, arm span, shoulder height, hip height, among others). Additionally, differences up to 12 centimeters were observed between the estimations of the segment lengths from the distal end of the hands to the proximal end of the thorax between the OMC and the IMC systems (with shorter segments on the IMC-based model), that difference in the segment lengths (lever arm) might result in lower moment estimates for the IMC model. Further research is needed on exploring the differences in segment lengths.

Another factor that might affect the variability between the models used in this study is the definition of the thorax as a single rigid segment for the TD calculations. In reality, the trunk is not a rigid body, so modeling the trunk as one is a potential source of error. When calculating moments from a BU approach, the Ground Reaction Forces (GRF) are the dominating factor, so the inertial properties are not as essential in the calculations; on the other hand, when estimating moments from a TD approach, the moment is mainly calculated using inertial properties. Hence, it would be expected to observe less accurate estimates when large body segment assumptions are in place (Desjardins et al., 1998; Plamondon et al., 1996).

The RMSE and ranges showed similar results to those previously observed in the literature (Faber et al., 2016, 2020; Koopman et al., 2018). When comparing the mean values of the ranges between the gold-standard OMC BU and the IMC TD for all trials (Table 2), the IMC TD moments were 13.14% smaller for the lifting tasks and 11.79% smaller for the lowering tasks.

It is also worth mentioning that the placement of the sacrum sensor for the IMU system was somewhat problematic due to the fact that there is not a prominent bony landmark that can be used for the IMU attachment point. We believe that due to the nature of the lifting and lowering tasks performed which required forward bending, the sacrum sensor could have moved (mostly upwards) from its original location, affecting the estimated moment results; this challenge has been identified before in the literature (Larsen et al., 2020; Schall et al., 2021).

Also, some outliers were present in the data; for instance, one of the subjects, whose anthropometry characteristics put them in the 99th percentile of the population, presented the highest moment estimates across all the different trials (with values around 60% larger than the mean). Further research is needed to understand the nature of the variability and the potential options to reduce it, which would make the IMU system promising for field-based risk assessment.

1.5 Limitations

One limitation of this study is the assumption of even weight distribution on the hands. It is not likely that a load's weight will be evenly distributed between both sides of the body, especially when loads present irregular geometries. Additionally, this approach does not consider the potential impact on pushing or pulling loads. Another limitation is associated with the individual characteristics of subjects. All the participants were young and healthy. IMC system performance might be affected with more obese participants, where more significant soft-tissue artifacts would be expected (Bolink et al., 2016). The participants were told to perform the lifting and lowering tasks with no restriction over the lifting technique and speed associated with the exertion; this might affect the variability of results (Fleron et al., 2019). Lastly, because the IMC data was captured on a per-trial basis (with trials lasting in general around half a minute), we did not observe major errors associated with magnetic disturbance and gyroscopic drift, which have been observed in the literature for longer trials (Robert-Lachaine et al., 2017) .

1.6 Conflict of interest statement

The authors certify that there is no conflict of interest with any organization regarding the material discussed in the manuscript

1.7 Acknowledgments

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1.9 Appendix

1.9.1 Appendix A – Consent form

AUBURN UNIVERSITY

SAMUEL GINN COLLEGE OF ENGINEERING
INDUSTRIAL AND SYSTEMS ENGINEERING

(NOTE: DO NOT SIGN THIS DOCUMENT UNLESS AN IRB APPROVAL STAMP WITH CURRENT DATES HAS BEEN APPLIED TO THIS DOCUMENT.)

INFORMED CONSENT
for a Research Study entitled
"Evaluation of a wireless sensor system for assessing cumulative lumbar loads in occupational settings"

You are invited to participate in a research study to evaluate a wireless sensor system for assessing cumulative lumbar loads in occupational settings. The study is being conducted by Dr. Sean Gallagher, PhD, CPE in the Auburn University Department of Industrial and Systems Engineering. You were selected as a possible participant because you are similar to an industrial worker.

To participate, you must be between 19 and 55 years of age with:

- No history of physician-diagnosed musculoskeletal disorders, injury, or surgery in the low back regions
- No chronic low back pain during the previous 6 months
- No physician-diagnosed neurodegenerative disease (e.g., Parkinson's disease, multiple sclerosis, etc.)
- Size 9-11 men's or a 10.5 - 12.5 women's shoes

This study is being performed to better understand the risk factors for developing musculoskeletal disorders among industrial workers. If you decide to participate in this research study, you will be asked to:

1. We will take measurements of the lengths and circumferences of several major links of your body (e.g., arm length) following established guidelines.
2. You will be fitted with a system of 17 small sensors and 30-40 reflective markers that will collect movement activity while you perform a simulated manual handling task (Figure 1). The sensors will be worn over each body segment including your trunk, arms, legs, and feet. The devices will be secured using a combination of elastic neoprene straps and hypoallergenic tapes.
3. You will be fitted with a sensor in each shoe that will monitor the pressure on your feet while you work. Total prep time will take 90-120 minutes.

Figure 1. Participant wearing IMU sensors and several motion capture markers.

The Auburn University Institutional Review Board has approved this Document for use from 07/24/2019 to 06/21/2020 Protocol # 16-211 MR 1606

Participant's initials _____ Page 1 of 3

SHELBY CENTER FOR ENGINEERING TECHNOLOGY
SUITE 3301
AUBURN, AL 36849-5346

TELEPHONE
334-844-4340

FAX:
334-844-1381

4. Once fitted with the sensor systems, you will perform a manual material handling task while we record your activity. The manual material handling task will involve moving boxes (similar to a standard milk crate) with handles containing a variety of loads (10, 20, or 30 lbs.) from the floor or a position at roughly knee height to a position at waist height and directly in front of you. The task will involve some minor torso twisting (up to 60 degrees) and will last approximately 45-60 minutes.

5. The manual material handling task will be performed on top of a force plate that is built into the ground. The force plate will measure the ground reaction forces you exert while performing the lifts. Your interaction with the force plate will be minimal.

6. Video recordings and still images of you may be captured to "spot check" the accuracy of the collected sensor data.
7. At the conclusion of the task, a research assistant will help you remove all of the sensors This will signify the end of you participation in this study

Your total time commitment will be approximately 3 hours.

Are there any risks or discomforts? The risks associated with participating in this study are minimal. No invasive or hazardous methods will be used to obtain data, and no treatments are offered. Removal of sensors may cause discomfort similar to removing a band aid. You may experience temporary redness around the sites where the sensors were placed. To minimize these risks, hypoallergenic tapes will be used to secure sensors to the skin to minimize the possibility of an allergic reaction. Movement of boxes may result in back or extremity muscle soreness or strain. These risks are similar to common occupational load movement tasks.

Are there any benefits to yourself or others? By participating in this study, you are contributing valuable information that may be used to develop interventions with the potential to mitigate exposures to physical risk factors and prevent adverse musculoskeletal conditions among industrial workers. We cannot promise you that you will receive any or all of the benefits described, but your contribution is greatly appreciated.

Will you receive compensation for participating? To thank you for your time, you will be paid $60 for your participation.

Participant's initials______

SAMUEL GINN COLLEGE OF ENGINEERING
INDUSTRIAL AND SYSTEMS ENGINEERING

Are you an Auburn University employee or a foreign national? Please be aware that compensation for participation in research may be subject to taxation. If you have any questions regarding taxation, please contact the Office of Procurement and Payment Services (334-844-7771).

Are there any costs? There are no costs associated with participating. Ifyou decide to participate, you will not be monetarily charged for anything. In the unlikely event that you sustain an injury from participation in this study, the investigators have no current plans to provide funds for any medical expenses or other costs you may incur.

What precautions have been taken? Study exclusion criteria prevent individuals with increased risk of injury from participating. Ample rest opportunities will be provided to you if requested. In the event of an emergency, a research team member who is present at the time will call emergency services (i.e., 911).

If you change your mind about participating, you can withdraw at any time during the study. Your participation is completely voluntary. If you choose to withdraw, your data can be withdrawn as long as it is identifiable. Your decision about whether or not to participate or to stop participating will not jeopardize your future relations with Auburn University or the Department of Industrial and Systems Engineering.

Your privacy will be protected. Any information obtained in connection with this study will remain anonymous. Information obtained through your participation may be published in a professional journal and/ or presented at a professional meeting. However, your identity will not be revealed and your information will remain completely private.

If you have questions about this study, please ask them now or contact Dr. Sean Gallagher, PhD, CPE, in the Auburn University Department of Industrial and Systems Engineering by calling (334) 734-2955 or by emailing seangallagher@auburn.edu. A copy of this document will be given to you to keep.

If you have questions about your rights as a research participant, you may contact the Auburn University Office of Research Compliance or the Institutional Review Board by phone (334)-844-5966 or e-mail at IRBadmin@auburn.edu or IRBChair@auburn.edu.

HAVING READ THE INFORMATION PROVIDED, YOU MUST DECIDE WHETHER OR NOT YOU WISH TO PARTICIPATE IN THIS RESEARCH STUDY. YOUR SIGNATURE INDICATES YOUR WILLINGNESS TO PARTICIPATE.

Participant's signature Date | Investigator obtaining consent Date

Printed Name | Printed Name

Participant's initials______

The Auburn University Institutional Review Board has approved this Document for use from 07/24/2019 to 06/21/2020 Protocol # 16-211 MR 1606

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1.9.2 Appendix A – Anthropometric form

Measurement	Posture	Reading (Metric units)
Body weight *	Standing	
Body height	Sitting	
Foot/ shoe length	Sitting	
Ankle height	Sitting	
Ankle width *	Sitting	
Knee height	Sitting	
Knee width *	Sitting	
Elbow width *	Sitting	
Shoulder width	Sitting	
Shoulder height	Standing	
Hip height	Standing	
Hip width	Standing	
Arm span	Standing	

Subject ID: Date:

Time:

* Additional Inputs.

Additional comments:

1.9.3 Appendix C – Eligibility questionnaire

Evaluation of a Wireless Sensor System for Assessing Cumulative Lumbar Loads in Occupational Settings	Industrial and Systems Engineering Department Auburn University 3301 Shelby Center Auburn, AL 36849 Tel: (334) 844-4340
This form is to be used for: Recruiting and initial screening of research subjects	

1. □ Yes □ No Are you feeling healthy and well today?

- Age (years): ___________________
- Shoe Size: ___________________

2. □ Yes □ No Do you or have you ever had a physician-diagnosed musculoskeletal disorder (MSD), injury, or surgery in the low back regions?
3. □ Yes □ No Have you had chronic low back pain during the previous 6 months?
4. □ Yes □ No Do you or have you ever had a physician-diagnosed neurodegenerative disease?

_______________________________________ _______________________________________

Participant's Signature Date Investigator's Signature Date

_______________________________________ _______________________________________

Participant's Printed Name Investigator's Printed Name

2. Scientific Report - Study 2: The Low Back Cumulative Trauma Index: A Fatigue-Failure Based Risk Assessment Tool.

ABSTRACT:

This study aimed to develop a systematic data processing framework that uses fatigue failure theory as the core method in estimating cumulative exposure with the ability to use continuous low-back loading information captured by Inertial Measurement Units (IMU) technology. Eight workers from an automotive manufacturing facility volunteered as participants, while they performed their regular work; L5/S1 moments were calculated using a top-down approach from a biomechanical model based on IMUs. A total of 108 trials were evaluated. Each trial corresponded to one complete working cycle of a specific car model at a particular workstation.

Low back injury recorded data provided by the company and self-reported injuries from surveys completed by the workers were compared against the model predicted risk using chi-square tests. As far as the authors know, this is the first attempt at estimating continuously accruing cumulative damage using a fatigue failure-based approach. The initial results are promising, the estimates of risk from the cumulative damage total showed a significant association with self-reported low back pain (χ^2 (df = 1, n = 108) = 5.01, p-value = 0.024), and with the low back injuries reported by the manufacturer (χ^2 (df = 1, n = 108) = 12.65, p-value < 0.001). In addition, results from stepwise logistic regression models showed a significant relationship between the cumulative damage estimates for the self-reported low-back pain (p = 0.002) and the recorded injuries (p = 0.038), respectively. In summary, the model provides flexibility in measuring cumulative damage estimation when dealing with different loads, postures, and occupational tasks observed in the field that could affect the development of occupational musculoskeletal disorders.

2.1 Introduction

Cumulative exposure to physical risk factors has been identified as a significant contributor to the development of MSDs in the workplace (Callaghan et al., 2001; Jäger et al., 2000; KUMAR, 1990; Norman et al., 1998). In order to better understand the relationship between exposure and health outcome, the ability to quantify cumulative exposure information is critical. Traditionally, practitioners would manually capture exposure information such as posture and forces by direct observation and/or review of video recordings (Burdorf et al., 1997; Spielholz et al., 2001).

Risk assessment tools are then used to estimate the level of risk based on that exposure. With advances in technology over the past decade, continuous measurement of exposure information has become much more accessible and affordable. Practitioners have taken advantage of new technologies to help capture exposure information in the workplace. As a result, large data sets may be generated. There is a need to develop systematic methods for using such information to better understand the relationship between cumulative exposure to physical risk factors and MSDs.

Recently, authors (Gallagher & Schall Jr., 2017) have summarized the evidence supporting the fatigue failure process in musculoskeletal tissues. The evidence includes ex vivo studies on tendons, ligaments, cartilage, and spinal motion segments. Results of in vivo animal studies examining the effects of repetitive loading on musculoskeletal tissues also report damage accumulation characteristic of a fatigue failure process (Andarawis-Puri & Flatow, 2011; Barbe et al., 2013, 2020; Fung et al., 2009, 2010; Sun et al., 2010). Studies have shown a decreasing exponential relationship between the stress applied and the number of cycles to material failure (Gallagher & Schall Jr., 2017). This relationship reveals that the impact of force and repetition is exponentially greater with higher stress in the development of cumulative damage.

In recent years, technology traditionally used in other fields has been introduced to occupational injury prevention. For example, motion capture systems that use inertial measurement units (IMU) have shown great potential in collecting postural exposure data in the field. External force measurement systems, such as force sensing insoles and smart gloves, have become more accessible and affordable. These new exposure information-capturing systems offer great potential for collecting objective data using standardized evaluation systems. This new generation of ergonomics risk evaluation technology shows promise in helping to provide greater insight into cumulative loading compared with traditional risk assessment tools like the Rapid Upper Limb Assessment (RULA), Rapid Entire Body Assessment (REBA) or the NIOSH Lifting Equation (Hignett & McAtamney, 2000; McAtamney & Nigel Corlett, 1993; Waters et al., 1994).

Fatigue failure theory may be ideally suited to leverage the new technologies, using a toolbox validated in the science of material engineering. This study aimed to use continuous low-back loading information captured by IMU technology to develop a systematic data processing framework that uses fatigue failure theory as the core method in estimating risk based on cumulative exposure.

2.2 Methods

2.2.1 Participants

A sample of eight subjects, six males and two females (ages between 19 to 64 years old; mean height = 174.17 cm ± 10.33 cm SD; mean body mass = 79.32 kg ± 10.61 kg SD) was recruited. Participants were workers from an automotive manufacturing facility. Inclusion criteria included 1) being an employee in the manufacturing facility, 2) no history of physician-diagnosed MSD, injury, or surgery in the low back, 3) no history of a physician-diagnosed neurodegenerative disorder that may affect movement (e.g., Parkinson's disease, multiple sclerosis, among others), and 4) Not presenting any health conditions that would put the person at heightened risk of severe illness from COVID-19, such as cancer, chronic kidney disease, chronic obstructive pulmonary disease, a weakened immune system due to an organ transplant, obesity (Body mass index, BMI, of 30 or higher), serious heart conditions, such as heart failure or coronary artery disease, sickle cell disease, or type 2 diabetes mellitus. Details about subjects' anthropometry are shown in Table 1. This study was reviewed and approved by the Institutional Review Board at Auburn University.

	Weight (kg)	Height (cm)	Shoe Length (cm)	Shoulder Height (cm)	Shoulder Width (cm)	Arm Span (cm)	Hip Height (cm)	Hip Width (cm)	Knee Height (cm)	Ankle Height (cm)
Mean	79.32	174.17	30.69	145.21	36.38	158.66	91.08	25.38	52.21	10.34
SD	10.61	10.33	2.42	8.60	4.05	52.19	7.17	2.63	4.34	0.96

Table 1. Summary of subjects' anthropometry (n = 8).

2.2.2 Types of Occupational Tasks

Manufacturing vehicles in the facility where this study occurred is a complex multistep process involving both automated and manual steps. The manual steps involve multiple repetitive movements, including bending at the waist to pick up/install parts, working above shoulder level, repetitive hand and wrist motion, and handling different loads which vary in weight and shape.

2.2.3 Epidemiological Evaluation

Epidemiological assessment of subjects was performed through the completion of a survey assessing low back disorders. Injury data from January 1st, 2018, through September 2nd, 2020, was provided by the facility, allowing the researchers to focus data collection on those lines and stations where injuries were previously observed. The primary guideline used to develop the surveys in this study was the Oswestry Disability Questionnaire (Fairbank JC & Pynsent P, 2000). Modifications were made during editing to reduce the potential risk for leading questions and survey complexity. The applied survey is in Appendix B.

Subjects completed the surveys individually. Employees were pulled out of their working lines for 25 to 45 minutes to complete surveys after the consenting process. They were asked to answer all questions honestly, following the survey instructions. Researchers were present only to provide clarification on instructions. If participants did not indicate low back pain (LPB), ache, or burning in the past year, they were allowed to skip the Oswestry Disability Questionnaire section of the survey as this questionnaire would not be relevant. When completing the surveys, it was made clear to all participants that specific individual data would not be shared with anyone outside the research team.

2.2.4 Biomechanical Assessment

2.2.4.1 Subject Preparation and Data Collection

After completing the informed consent process following Auburn University and the manufacturer guidelines, data collection started. Videos were recorded by two research team members while subjects performed their tasks. Subjects were fitted with 17 IMUs (MVN Awinda, Xsens Technologies B.V., Enschede, Netherlands). Each IMU is a small, wireless, battery-powered unit that measures and stores acceleration, angular velocity, and magnetic field information. The sensors were secured using a combination of elastic neoprene straps and/or hypoallergenic athletic tape (Figure 1). Anthropometric measurements were used to build a rigid link biomechanical model using the information collected from the IMU sensors.

2.2.4.2 Systems Calibration

Before the task completion, subjects were required to follow calibration protocols for the Inertial Motion Capture (IMC) system. Segment calibration on the IMC system is necessary to align the motion trackers to the subject segments (Xsens®, 2021). The procedure consists of each subject holding a neutral posture for a few seconds (N-pose), then walking forward and turning around and walking back to the point where they started.

Figure 1. Subject working at a station while wearing the IMU sensors

2.2.4.3 Data Cleaning and Processing

IMC data was sampled at 60Hz. Force and kinematic data were bi-directionally low-pass filtered with a second-order Butterworth filter at 5 Hz for the IMC system (Faber et al., 2020). Trials were smoothed using a moving average of 10 frames as an additional measure to reduce noise in the data captured.

2.2.4.4 Experimental Procedure

The participants were instructed to perform their manual material handling jobs as they would typically do them; they were also instructed to inform the team if they noticed any difference when performing their tasks because of the IMU sensors. Each subject worked on a particular production line, typically cycling through five different stations on average during a given eight-hour shift. Three car models were manufactured while the research team collected data at the plant. In order to ensure quality data, data was captured at least twice for each of the 3 models for each worker for every station they were working.

2.2.4.5 Biomechanical Modeling

Inverse dynamics were calculated by employing a top-down analysis approach to analyze the data. The 15-segment biomechanical model for the IMC system data analysis, was developed by the biomechanical analysis software Visual3D to use within their software (C-Motion®, 2020). For the Top-Down model, external loads were assigned to the hands when the subjects were lifting, lowering or carrying the loads (using recorded videos and the IMC visual representations); if loads were handled with two hands, the load was assumed to be divided evenly between them. Total moments were calculated for the analyses. The total moment is the vector summation of each plane's L5/S1 moments (X, Y, Z).

2.2.4.6 Task Identification

Videos of each subject's work postures and activities were recorded while performing their work with the IMU sensors. Two camcorders were used for recording to ensure the analysis of all work postures could be identified from at least two angles. These videos also provided a method to cross-reference biomechanical data. A video-based job analysis was independently performed by two researchers. First, worker postures and movements were analyzed by observational methods. Various work postures were defined and characterized for different body regions, including the shoulder, wrist, back, neck, and leg. Upper extremity postures, such as grasping and pinching, were identified. Awkward postures included reaching, body twisting, bending, neck twisting, hyper-extended or flexed back positions, overhead work, and kneeling. The researchers defined manual material handling tasks as lifting/lowering, horizontal pulling/pushing, and forward pulling/pushing. Also, handheld tools were often used as part of the work tasks studied; thus, researchers also observed hand-arm vibration exposure during biomechanical data collection. However, this was not considered in the subsequent analysis. As the majority of work was attaching parts to cars, the team also obtained the weights of both handled parts and hand-held tools, which were essential to the biomechanical analysis. Repetition and duration of each task were also analyzed for each subject.

2.2.5 Data Processing Framework

A data processing framework is presented in Figure 2 on the following page. It starts with exposure information, including posture and external force. Postural data was collected using a motion capture system, manual or computerized video analysis, and observation. External forces were collected through instrumented devices, including force transducers and pressure sensing insoles, direct measurement of contacting objects, and observational estimation. Using these inputs, simplified or more complex dynamic biomechanical models can be applied to estimate continuous low back stresses such as moments and compression forces.

Rainflow counting techniques (Matsuishi & T. Endo, 1968) can be used to analyze continuous low back loading data and produce a "real-time" profile of the exposure distribution associated with a number of cycles using estimates of the stress (or force, moment) range; and the mean stress (or force, moment). Using the technique damage due to each loading cycle was estimated and summed (cumulative damage). Risk estimation was based on this cumulative damage value. Figure 2 on the next page provides a graphic describing this process.

2.2.5.1 Rainflow Cycle Counting

Rainflow cycle counting is a well-established and applied technique in material fatigue analysis (Matsuishi & T. Endo, 1968). It generates a loading profile for the time history of stresses (force, torque, etc.) by providing the number of times cycles of various sizes occur. The American Society has documented detailed instructions on rainflow cycle counting for Testing and Materials (ASTM E1049-85, 2017). The authors completed the rainflow analysis using Microsoft Excel tools (TL Anderson Consulting, n.d.).

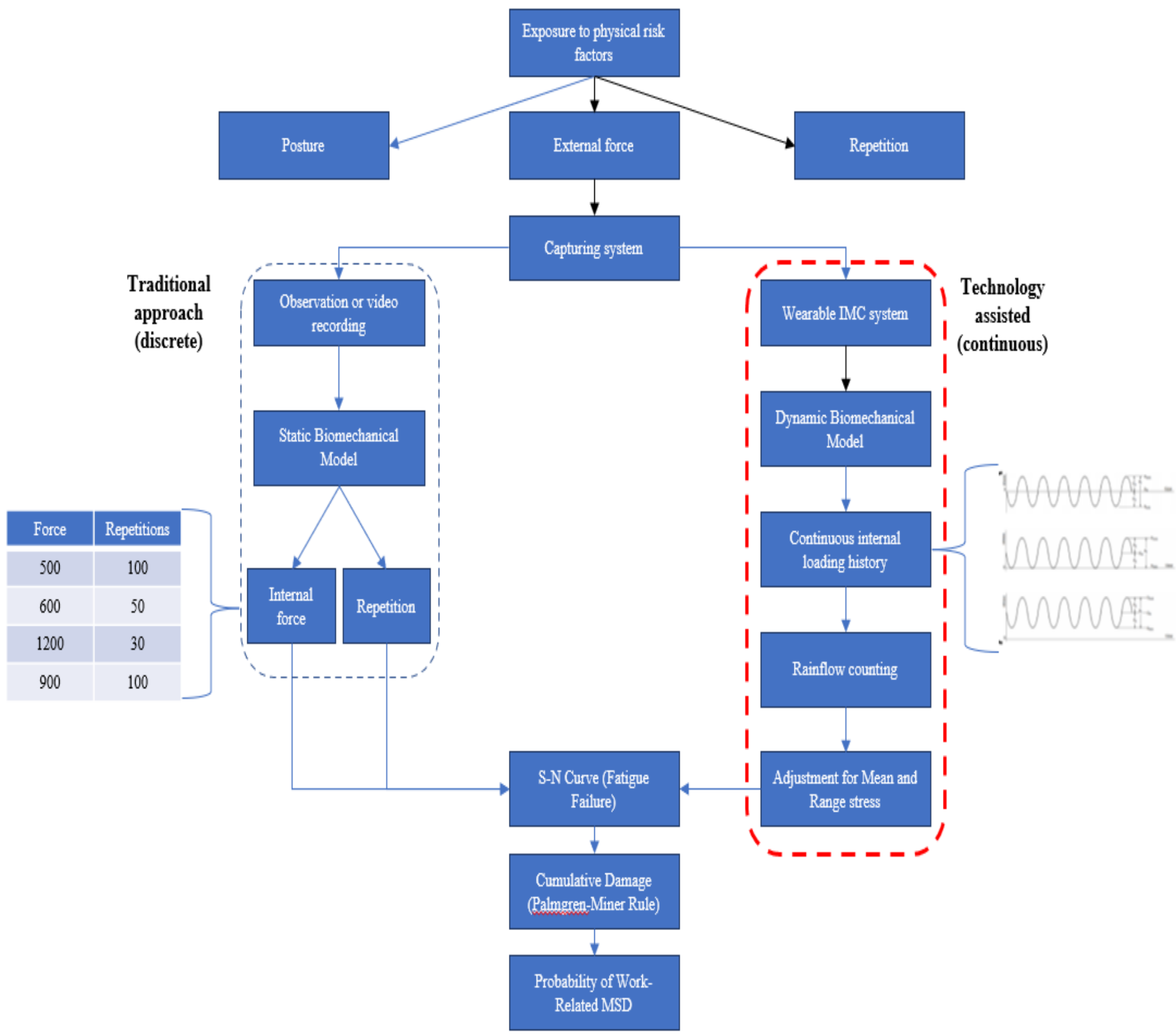

Figure 2. Traditional versus technology-assisted framework to data processing using fatigue failure methods

2.2.5.2 Cycle Loading Damage Estimation

The relationship between the level of stress and cycles to failure for cadaveric lumbar spines was characterized (Gallagher et al., 2017) based on different studies (Brinckmann et al., 1987; Gallagher et al., 2005, 2007). It revealed a similar exponential relationship (Equation 1) between the stress level experienced and the number of cycles to failure compared with other materials such as metals.

Equation 1:

$$N = 1{,}099{,}097.56 \times e^{-0.122 \text{ x } \%US}$$

Where:

N = number of cycles to failure.

%US = percentage of the ultimate strength for a motion segment.

The loading pattern for the spine can be categorized as “fluctuating stress” since the human spine is usually under a certain level of compressive load due to body weight while in standing and sitting postures. Thus, the stress amplitude and mean stress designed for fully reversed sinusoidal loading need to be adjusted. Therefore, each pair of mean stress and stress range was used to adjust for the revised stress amplitude based on Goodman’s (Equation 2) method.

Equation 2:

$$\frac{S_a}{S_{Nf}} + \frac{S_m}{S_u} = 1$$

Where:

S_a = alternating stress.

S_m = the mean stress.

S_{Nf} = the estimated value of the stress at failure for exactly *Nf* cycles as determined by an S-N diagram.

S_u = the ultimate stress.

This revised stress amplitude was used to represent the stress level for each repetition categorized by the rainflow cycle counting technique. Together with (Equation 1), the number of cycles to failure for each stress amplitude can be estimated. This allows damage for each loading cycle to be calculated. Cumulative damage for a series of loading cycles can then be estimated by applying the Palmgren-Miner rule (Equation 3) which is the most used model of estimating or predicting damage resulting from spectrum loading (A., 1924; Miner, 1945).

Equation 3:

$$c = \sum_{i}^{k} \frac{n_1}{N_1} + \frac{n_2}{N_2} + \cdots \frac{n_k}{N_k}$$

Where:

c is a constant (often set at 1, but which may vary).

n_i … is the number of loading cycles experienced at force levels at which N_i … cycles would result in material fatigue failure.

2.2.6 Statistical Analysis

Chi-square tests of independence and stepwise logistic regression tests were performed to examine the relationship between reported low-back pain and recorded injury data to the estimates from the continuous fatigue failure assessment method. A significance level of 0.05 was used for all tests. Statistical tests were conducted in Minitab® (version 19.2020.1, LLC, USA).

2.3 Results

Workers who participated in the study worked on eight different production lines and 49 different stations with three or two car models in production during the site visits, depending on the day’s schedule. The research team collected data for a total of 108 trials (one trial is one the work performed per car model, per station, per line).

2.3.1 Example of the Continuous Fatigue Failure-based Risk Assessment Model

In this example, a worker performed his job at one of the trimming stations; the only external load associated with this trial is a pneumatic rachet (1.5 kg, handled with the right hand). The estimated total moment is shown in Figure 3. The duration of the task is one minute.

With the moment loading history associated with the exertions performed at that workstation when manufacturing a particular car model, forces at L5/S1 level were estimated using a lever arm for the erector spinae muscle of 5 cm (Chaffin et al., 2006). The line of action of the erector spinae muscles was assumed to act parallel to the normal compression force on the L5/S1 disc.

Next, the obtained forces were applied to an average cross-sectional area of 16.2 cm of the L5/S1 disc (Jager M & Luttmann A, 1991) to get the corresponding stress loading history. The stress loading history was processed using the rainflow analysis to obtain the number of cycles, mean and range for the stress history. Using Goodman's method, the stress magnitudes were adjusted based on the stress range and mean stresses (Equation 2). Then, the revised stress ranges are used to calculate damage per loading cycle, using the average ultimate strength for a 35-year-old male (closest estimate to the average worker who participated in the study) of 7.3 kN (4.51 MPa) (Jager M & Luttmann A, 1991).

The cumulative damage was calculated using the Palmgren-Miner rule (Equation 3), adding up the individual cycles. After obtaining estimates of cumulative damage, the final result corresponding to an average workday is obtained by multiplying the cumulative damage by 480 (8 hours of work, the working period at the manufacturing facility).

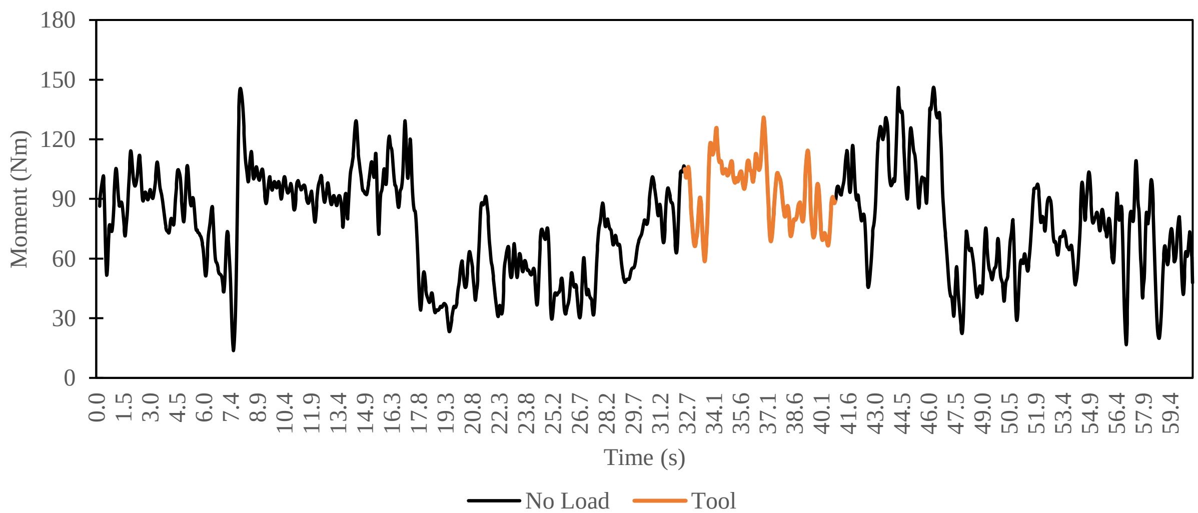

Figure 3. Example of the estimated total moment.

Lastly, if the result is greater than or equal to 1.0, the worker would be considered at increased risk of a low-back injury because the cumulative damage would be higher than the critical threshold. An example of the adjusted stress range loading history after applying the rainflow cycle counting method is shown in Figure 4.

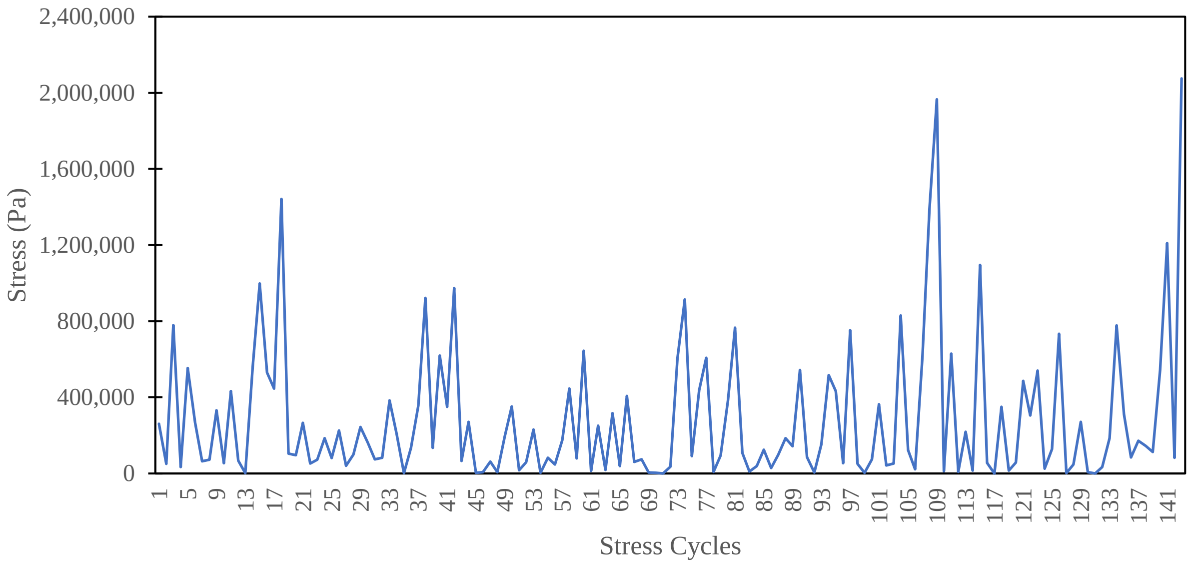

Figure 4. Stress range adjusted by compression after applying rainflow analysis

2.3.2 Summary of Results

Among the subjects who completed the surveys, four reported low-back pain, while the other four did not. Pain severity was not a factor considered to further classify the injuries. From the total 108 processed trials, the results from the biomechanical assessment were the following, 90 trials were not considered as risky by the continuous fatigue failure assessment method. In contrast, the remaining 18 were at high risk of low-back injury because their final estimates were above the critical threshold of 1.0. Detailed results from the cumulative damage estimates, recorded injury data provided by the manufacturer, and self-reported low-back pain from the workers' surveys can be found in Appendix A. Table 2 and 3 show the results data used for comparison on each analysis.

		Did the model predict injury?		
		Yes	No	Total
Was there a self-reported injury?	Yes	6	5	11
	No	12	85	97
	Total	18	90	108

Table 2. Summary of results for the comparison of low-back pain and the fatigue failure model predicted risk

		Did the model predict injury?		
		Yes	No	Total
Was there a recorded injury?	Yes	13	39	52
	No	5	51	56
	Total	18	90	108

Table 3. Summary of results for the comparison of recorded injuries and the fatigue failure model predicted risk

2.3.3 Statistical Analysis

A chi-square test of independence was performed to examine the relationship between the self-reported low-back pain and the risk estimates obtained from the cumulative damage calculated using the novel fatigue failure-based continuous assessment method. Results indicate that there is a significant relationship between the two variables. Self-reported low-back pain and high (greater or equal to 1.0) cumulative damage estimates showed a significant association, χ^2 (df = 1, n = 108) = 5.01, p-value = 0.024.

Additionally, another chi-square test of independence was performed to examine the relationship between the recorded injury data provided by the manufacturer and the risk estimates obtained from the cumulative damage estimations. As with self-reported low-back pain, results indicate a significant relationship between the two variables. The presence of injuries and high (greater or equal to 1.0) cumulative damage estimates showed a significant association, χ^2 (df = 1, n = 108) = 12.65, p-value < 0.001.

Results from the logistic regression performed to ascertain the relationship between the cumulative damage (CD) and the injury data (recorded and self-reported) after including in the model the subjects, lines, and stations as covariates, showed significant results for both variables, respectively, with a p-value of 0.038 for the CD when evaluated with respect to the recorded injuries provided by the company, and a p-value of 0.002 for the CD, when evaluated with respect to the self-reported low back pain recorded injuries.

2.4 Discussion

This study is the first attempt to demonstrate the use of a first fatigue failure-based continuous risk assessment method with the capability to accommodate low back compressive force history generated using a biomechanical model fed by an inertial motion capture system. The model provides flexibility in the measurement of cumulative damage estimation when dealing with different loads, postures and occupational tasks observed in the field that could affect the development of occupational musculoskeletal disorders.

The initial results for this first attempt at estimating continuously cumulative damage using a fatigue failure-based approach are promising, as the estimates of risk from the cumulative damage total showed a significant association with self-reported low back pain and with the low back injuries reported by the manufacturer, for both chi-square tests of independence and stepwise logistic regression analyses.

The external loads workers were handling on their respective lines and stations were between one to three kilograms on average (with a few exceptions of car parts weighing around 10 kg). An interesting observation of our results was the impact of posture on the assessment of risk. A large number of stations with high estimates of cumulative damage and reported injuries showed workers performing tasks in awkward postures, especially involving torso flexion. Those sub-tasks where significant torso flexion was observed coincidentally showed high peak moments, which highlights the importance of considering the impact of posture when estimating cumulative damage.

This method can also account for personal characteristics like sex or age, which affect critical factors in our analysis, like cross-sectional areas of the L5-S1 disc and the ultimate strength of the spine (Jager M & Luttmann A, 1991). Additional adjustments for workers personal characteristics can be added in the future; further research is needed to validate these potential improvements.

Even though is beyond this project's scope, the research team collected some preliminary shoulder and upper extremity epidemiological data that could be used for further research. This approach could be applied for other body parts, for example the shoulders or the upper extremities, where there are data that could be utilized as a reference for the ultimate strength of tendons on fatigue failure-based discrete risk assessment tools already published in the literature (Bani Hani et al., 2021; Gallagher et al., 2018). For example, having injury data and biomechanical estimates of shoulder forces, which could be obtained from a musculoskeletal biomechanical modeling software like Anybody™ modeling system (Aurbach et al., 2020; Damsgaard et al., 2006), would allow us to replicate and adapt the modeling approach presented on these pages.

2.5 Limitations

The COVID-19 pandemic significantly affected the performance of this research project, from the cooperator having a constant workforce shortage which did not allow the team to capture data from some of the lines and stations that were initially planned, to the anticipated final closeout of the data collection because of outbreaks at the manufacturing facility. Ending the data collection early affected the study's aimed sample size and posterior analysis; still, the significant results from our analysis make further research promising.

One limitation of this study is the assumption of even weight distribution on the hands. It is not likely that a load's weight will be evenly distributed between both sides of the body, especially when loads present irregular geometries. Additionally, this approach does not consider the potential impact on pushing or pulling loads. Another limitation is associated with the individual characteristics of subjects. The IMC system performance might be affected by more obese participants, a substantial number of adults in the United States (Ogden et al., 2014), where more significant soft-tissue artifacts would be expected (Bolink et al., 2016).

Also, because the IMC data was captured on a per-trial basis (with trials lasting around a minute), we did not observe major errors associated with magnetic disturbance and gyroscopic drift, which have been observed in the literature for longer trials (Robert-Lachaine et al., 2017). It is also worth mentioning that the research team was recalibrating the IMC system between stations, which could help preventing gyroscopic drift according to the system's manufacturer.

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2.7 Conflict of Interest Statement

The authors certify that there is no conflict of interest with any organization regarding the material discussed in the manuscript

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2.9 Appendix

2.9.1 Appendix A – Table with Subjects' respective working lines, stations, and injuries reported from the manufacturer and the completed surveys. Cumulative damage estimates greater or equal to 1.0 represent a predicted high risk job.

Subject	Line	Station	Injury Reported **(0 = No, 1 = Yes)**	Survey Reported **(0 = No, 1 = Yes)**	Model	Cumulative Damage Day
S01	1	1L	0	1	1	0.417
S01	1	1L	0	1	2	0.297
S01	2	2L	0	1	3	0.783
S01	2	2L	0	1	2	0.545
S01	2	2L	0	1	1	0.125
S01	1	3L	0	1	2	1.323
S01	1	3L	0	1	1	0.799
S01	3	7L	0	1	1	0.114
S01	3	7L	0	1	3	0.108
S01	3	7L	0	1	2	0.102
S01	3	14L	0	1	2	0.170
S01	3	14L	0	1	1	0.114
S01	3	14L	0	1	3	0.129
S02	4	6R	0	0	2	0.691
S02	4	6R	0	0	1	0.413
S02	4	6R	0	0	3	0.410
S02	4	13L	0	0	2	0.490

S02	4	13L	0	0	3	0.418
S02	4	13L	0	0	1	0.411
S02	4	13R	0	0	3	1.280
S02	4	13R	0	0	1	0.979
S02	4	13R	0	0	2	0.990
S02	4	14L	0	0	3	4.454
S02	4	14L	0	0	2	1.721
S02	4	14L	0	0	1	0.767
S02	4	16R	0	0	2	0.545
S02	4	16R	0	0	1	1.686
S02	4	16R	0	0	3	0.781
S03	5	8L	0	0	2	0.160
S03	5	8L	0	0	3	0.155
S03	5	8L	0	0	1	0.133
S03	5	11L	0	0	2	0.786
S03	5	11L	0	0	3	0.341
S03	5	11L	0	0	1	0.338
S03	5	13R	1	0	3	1.323
S03	5	13R	1	0	2	0.768
S03	5	13R	1	0	1	0.313
S03	5	14R	0	0	3	0.267
S03	5	14R	0	0	1	0.242
S04	6	7L	1	1	2	3.309
S04	6	7L	1	1	1	2.252
S04	6	7R	0	1	1	1.572
S04	6	7R	0	1	2	0.940
S04	6	8L	0	1	2	4.166
S04	6	8L	0	1	1	4.246
S04	6	8R	0	1	1	4.508
S04	6	8R	0	1	2	3.588
S04	6	9L	0	1	1	0.938
S04	6	9L	0	1	2	0.366
S04	6	9R	0	1	2	0.950
S04	6	9R	0	1	1	0.545
S05	7	2R	0	0	2	0.189
S05	7	2R	0	0	1	0.132
S05	7	5R	0	0	2	0.231
S05	7	5R	0	0	1	0.143
S05	7	8L	0	0	1	0.171
S05	7	8L	0	0	2	0.135
S05	7	9L	0	0	2	0.991
S05	7	9L	0	0	1	0.189
S05	7	11R	0	0	1	0.350
S05	7	11R	0	0	2	0.088
S05	7	16R	0	0	1	0.545
S05	7	16R	0	0	2	0.140
S06	8	16R	0	1	3	0.157
S06	8	16R	0	1	2	0.116
S06	8	16R	0	1	1	0.108
S06	8	18R	0	1	2	0.130
S06	8	18R	0	1	1	0.133
S06	8	18R	0	1	3	0.136
S06	8	21R	0	1	2	0.713
S06	8	21R	0	1	3	0.187
S06	8	21R	0	1	1	0.162
S06	8	24R	0	1	2	0.114
S06	8	24R	0	1	3	0.121
S06	8	24R	0	1	1	0.099
S07	6	1L	0	1	1	1.534
S07	6	1L	0	1	2	1.114
S07	6	1L	0	1	3	0.384
S07	6	1R	0	1	2	0.424

S07	6	1R	0	1	1	0.249
S07	6	1R	0	1	3	0.196
S07	6	3L	0	1	3	0.261
S07	6	3L	0	1	1	0.155
S07	6	3L	0	1	2	0.077
S07	6	3R	0	1	2	0.307
S07	6	3R	0	1	3	0.283
S07	6	3R	0	1	1	0.179
S07	6	7L	1	1	3	3.344
S07	6	7L	1	1	2	3.193
S07	6	7L	1	1	1	1.827
S08	4	1L	0	0	1	0.162
S08	4	1L	0	0	3	0.127
S08	4	1L	0	0	2	0.138
S08	4	1R	0	0	3	0.206
S08	4	1R	0	0	1	0.196
S08	4	1R	0	0	2	0.134
S08	4	2R	0	0	3	0.167
S08	4	2R	0	0	2	0.150
S08	4	2R	0	0	1	0.133
S08	4	10L	1	0	1	0.299
S08	4	10L	1	0	2	0.137
S08	4	10L	1	0	3	0.149
S08	4	10R	0	0	3	0.287
S08	4	10R	0	0	1	0.264
S08	4	10R	0	0	2	0.202
S08	4	13R	0	0	3	0.611
S08	4	13R	0	0	1	0.114
S08	4	13R	0	0	2	0.082

2.9.2 Appendix B – Low-Back Survey.

Subject ID ___________________________ Date ________/________/________
Month Day Year

Low Back Data Collection Elements

1. Have you **ever** been seen by a health care professional (medical doctor, physical therapist, chiropractor) for pain in your Low Back?
   ___ Yes ___ No

2. Have you seen a health care professional (such as a doctor, physical therapist, chiropractor) for Low Back Pain **in the past year**?
   ___ Yes ___ No

3. Have you **ever** had surgery on your Low Back?
   ___ Yes ___ No

   a. If yes, please tell us the name of the surgery, describe the surgery, which side (right, left) and the approximate year.
   ____
   ____
   ____
   ____

4. Have you **ever** taken a prescription medication for your Low Back Pain?
   ___ Yes ___ No

5. Have you **ever** used an over-the-counter treatment (like aspirin, ibuprofen, icy-hot, ice-pack, heating pad) for Low Back Pain?
   ___ Yes ___ No

6. Have you **ever** been told by a health care professional (medical doctor/chiropractor) that you have Osteoarthritis or Degenerative Arthritis in the low back(s)?
   ___ Yes ___ No

7. Did you ever hurt your low back when you were younger?
   ___ Yes ___ No

   a. If yes, what was it?
   ___ Car crash
   ___ Sports Injury
   ___ Fall
   ___ Other (please describe)__________________________________

   b. Did you fully recover from this injury? ___ Yes ___ No ___Unsure

Subject ID ____________________________ Date ________/________/________
Month Day Year

PAIN ASSESSMENT

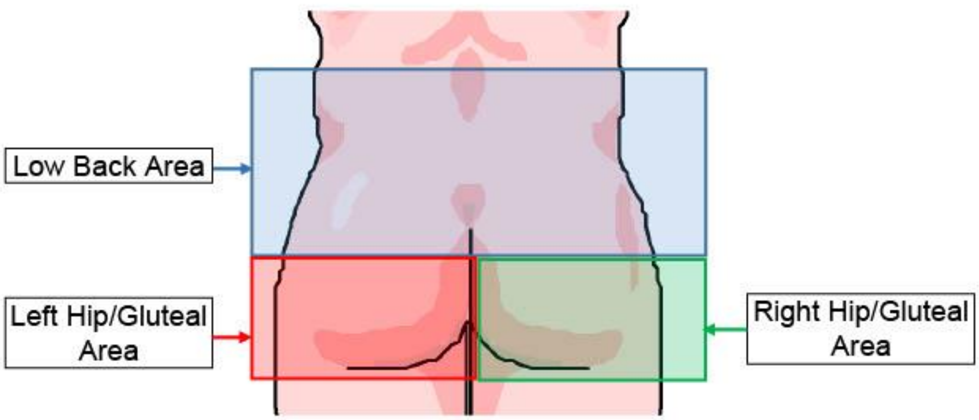
8. Have you had any low back pain in the **past year**? (IF NO, SKIP TO QUESTION 19)
___ Yes ___ No

9. Place an "X" on the line at the place that represents the **worst** low back pain you have had in the **past year**.

No Pain ____ **Worst Pain Imaginable**

10. At the current time or at any time in the **past month** have you had any pain, ache, and/or burning, in any of the following body parts? (**check all that apply** and refer to the body diagram if needed).

Body part	Yes	No	Pain / Ache / Burning in this body part **in the past month**	Please Circle the **Pain** Severity Rating at it's worst **in the past month** (0 is no pain-10 worst pain)											Do you **currently** (today) have Pain / Ache / Burning Symptoms
Low Back			☐ Pain ☐ Ache ☐ Burning	0	1	2	3	4	5	6	7	8	9	10	☐Yes ☐No
Right Hip/Gluteal			☐ Pain ☐ Ache ☐ Burning	0	1	2	3	4	5	6	7	8	9	10	☐Yes ☐No
Left Hip/Gluteal			☐ Pain ☐ Ache ☐ Burning	0	1	2	3	4	5	6	7	8	9	10	☐Yes ☐No



Subject ID ___________________________ Date _________/_________/_________
Month Day Year

How severe is your pain?
Circle the number that best describes your pain where:
0 = no pain and 10 = the worst pain imaginable.

	No pain									Worst pain	
11. When lying on your side (right or left)?	0	1	2	3	4	5	6	7	8	9	10	N/A
12. Reaching for something on a high shelf?	0	1	2	3	4	5	6	7	8	9	10	N/A
13. Bending over forward?	0	1	2	3	4	5	6	7	8	9	10	N/A
14. Bending to the side?	0	1	2	3	4	5	6	7	8	9	10	N/A
15. Twisting?	0	1	2	3	4	5	6	7	8	9	10	N/A

16. Have you been off of work (lost time) for low back pain in the past year?
___ Yes ___ No

17. Have you changed your work practices (modified duty) for low back pain in the past year?
___ Yes ___ No

18. What do you think was the cause of your low back pain? If it was a single event, please describe what happened. If it is something that happened over time, please describe what that progression was like. You can also answer unsure.

____
____
____
____
____
____
____
____
____
____

For each statement please **circle** the number from 0 to 6 to indicate how much **physical activities** such as bending, lifting, walking or driving affect or would affect your back pain.

	Completely Disagree			Unsure			Completely Agree
19. Physical activity makes my pain worse.	0	1	2	3	4	5	6
20. Physical activity might harm my low back.	0	1	2	3	4	5	6
21. I should not do physical activities which (might) make my pain worse.	0	1	2	3	4	5	6
22. I cannot do physical activities which (might) make my pain worse.	0	1	2	3	4	5	6

Subject ID ____________________________ Date _________/_________/_________
Month Day Year

The following statements are about how your **normal work** affects or would affect your back pain.
For each statement please **circle** the number from 0 to 6.

	Completely Disagree			Unsure			Completely Agree
23. My low back pain was caused by my work or by an accident at work.	0	1	2	3	4	5	6
24. My work aggravated my low back pain.	0	1	2	3	4	5	6
25. My work is too heavy for me.	0	1	2	3	4	5	6
26. My work makes or would make my low back pain worse	0	1	2	3	4	5	6
27. My work might harm my low back.	0	1	2	3	4	5	6
28. I should **not** do my regular **work** with my present pain.	0	1	2	3	4	5	6
29. I **do not** think that I will be return to or at my normal **work level** within 3 months.	0	1	2	3	4	5	6

Oswestry Disability Questionnaire

This questionnaire has been designed to give us information as to how your back pain has affected your ability to manage everyday-life activities. Please answer every section, and mark in each section the **one statement** that applies to you. We realize you may consider that two of the statements in any one section relate to you, but please just mark the box that most clearly describes your present-day situation

30. **PAIN INTENSITY (PLEASE CHOOSE ONE)**

____ My pain is mild to moderate; I do not need painkillers.
____ The pain is bad, but I manage without taking painkillers.
____ Painkillers give complete relief from pain.
____ Painkillers give moderate relief from pain.
____ Painkillers give very little relief from pain.
____ Painkillers have no effect on the pain.

31. **PERSONAL CARE (PLEASE CHOOSE ONE)**

____ I can look after myself normally without causing extra pain.
____ I can look after myself normally, but it causes extra pain.
____ It is painful to look after myself, and I am slow and careful.
____ I need some help but manage most of my personal care.
____ I need help every day in most aspects of self-care.
____ I do not get dressed. I wash with difficulty and stay in bed.

Subject ID ____________________________ Date _________/_________/_________
Month Day Year

32. **LIFTING (PLEASE CHOOSE ONE)**

____ I can lift heavy weights without causing extra pain.
____ I can lift heavy weights, but it gives me extra pain.
____ Pain prevents me from lifting heavy weights off the floor, but I can manage if items are conveniently positioned, i.e. on the table.
____ Pain prevents me from lifting heavy weights, but I can manage light weights if they are conveniently positioned.
____ I can lift only very light weights.
____ I cannot lift or carry anything at all.

33. **WALKING (PLEASE CHOOSE ONE)**

____ I can walk as far as I wish.
____ Pain prevents me from walking more than 1 mile.
____ Pain prevents me from walking more than 1/2 mile.
____ Pain prevents me from walking more than 1/4 mile.
____ I can walk only if I use a cane or crutches.
____ I am in bed or in a chair for most of every day.

34. **SITTING (PLEASE CHOOSE ONE)**

____ I can sit in any chair for as long as I like.
____ I can sit in my favorite chair only, but for as long as I like.
____ Pain prevents me from sitting for more than 1 hour.
____ Pain prevents me from sitting for more than 1/2 hour.
____ Pain prevents me from sitting for more than 10 minutes.
____ Pain prevents me from sitting at all.

35. **STANDING (PLEASE CHOOSE ONE)**

____ I can stand as long as I want without extra pain.
____ I can stand as long as I want, but it gives me extra pain.
____ Pain prevents me from standing for more than 1 hour.
____ Pain prevents me from standing more than 1/2 hour.
____ Pain prevents me from standing more than 10 minutes.
____ Pain prevents me from standing at all.

36. **SLEEPING (PLEASE CHOOSE ONE)**

____ Pain does not prevent me from sleeping well.
____ I sleep well, but only when taking medication.
____ Even when I take medication, I sleep less than 6 hours.
____ Even when I take medication, I sleep less than 4 hours.
____ Even when I take medication, I sleep less than 2 hours.
____ Pain prevents me from sleeping at all.

Subject ID ____________________________ Date _________/_________/_________
Month Day Year

37. **SOCIAL LIFE (PLEASE CHOOSE ONE)**
- ____ My social life is normal and causes me no extra pain.
- ____ My social life is normal, but increases the degree of pain.
- ____ Pain affects my social life by limiting only my more energetic interests, such as dancing, sports, etc.
- ____ Pain affects my social life, and I do not go out as often.
- ____ Pain has restricted my social life to my home.
- ____ I have no social life because of pain.

38. **TRAVELING (PLEASE CHOOSE ONE)**
- ____ I can travel anywhere without extra pain.
- ____ I can travel anywhere, but it gives me extra pain.
- ____ Pain is bad, but I manage journeys over 2 hours.
- ____ Pain restricts me to journeys of less than 1 hour.
- ____ Pain restricts me to necessary journeys under 1/2 hour.
- ____ Pain prevents traveling except to the doctor/hospital.

39. **CHANGING DEGREE OF PAIN (PLEASE CHOOSE ONE)**
- ____ My pain is rapidly getting better.
- ____ My pain fluctuates but overall is definitely getting better.
- ____ My pain seems to be getting better but improvement is slow at present.
- ____ My pain is neither getting better nor worse.
- ____ My pain is gradually worsening.
- ____ My pain is rapidly worsening.

Pain Interference

Please respond to each question or statement by marking **one** box per row.

In the past 7 days…	Not at all	A little bit	Somewhat	Quite a bit	Very much
40. How much did pain interfere with your day to day activities?					
41. How much did pain interfere with work around the home?					
42. How much did pain interfere with your ability to participate in social activities?					
43. How much did pain interfere with your household chores?					
44. How much did pain interfere with the things you usually do for fun?					
45. How much did pain interfere with your enjoyment of social activities?					

Subject ID ___________________________ Date ________/________/________
Month Day Year

Everyone experiences painful situations at some point in their lives. Such experiences may include headaches, tooth pain, joint or muscle pain. People are often exposed to situations that may cause pain such as illness, injury, dental procedures or surgery.

We are interested in the types of thoughts and feelings that you have when you are in pain. Listed below are thirteen statements describing different thoughts and feelings that may be associated with pain. Using the following scale, please indicate the degree to which you have these thoughts and feelings when you are experiencing pain.

When I'm in pain ...

46. I worry all the time about whether the pain will end.
   ___ Not at all
   ___ To a slight degree
   ___ To a moderate degree
   ___ To a great degree
   ___ All the time
   ___ N/A

47. I feel I can't go on.
   ___ Not at all
   ___ To a slight degree
   ___ To a moderate degree
   ___ To a great degree
   ___ All the time

48. It's terrible and I think it's never going to get any better.
   ___ Not at all
   ___ To a slight degree
   ___ To a moderate degree
   ___ To a great degree
   ___ All the time

49. It's awful and I feel that it overwhelms me.
   ___ Not at all
   ___ To a slight degree
   ___ To a moderate degree
   ___ To a great degree
   ___ All the time

50. I feel I can't stand it anymore.
   ___ Not at all
   ___ To a slight degree
   ___ To a moderate degree
   ___ To a great degree
   ___ All the time

51. I become afraid that the pain will get worse.
   ___ Not at all
   ___ To a slight degree
   ___ To a moderate degree
   ___ To a great degree
   ___ All the time

Subject ID ____________________________ Date ________/________/________
Month Day Year

52. I keep thinking of other painful events.
___ Not at all
___ To a slight degree
___ To a moderate degree
___ To a great degree
___ All the time

53. I anxiously want the pain to go away.
___ Not at all
___ To a slight degree
___ To a moderate degree
___ To a great degree
___ All the time

54. I can't seem to keep it out of my mind.
___ Not at all
___ To a slight degree
___ To a moderate degree
___ To a great degree
___ All the time

55. I keep thinking about how much it hurts.
___ Not at all
___ To a slight degree
___ To a moderate degree
___ To a great degree
___ All the time

56. I keep thinking about how badly I want the pain to stop.
___ Not at all
___ To a slight degree
___ To a moderate degree
___ To a great degree
___ All the time

57. There's nothing I can do to reduce the intensity of the pain.
___ Not at all
___ To a slight degree
___ To a moderate degree
___ To a great degree
___ All the time

58. I wonder whether something serious may happen.
___ Not at all
___ To a slight degree
___ To a moderate degree
___ To a great degree
___ All the time

Subject ID ____________________________ Date ________/________/________
Month Day Year

Please indicate which statements best describe your own health state **today**.

59. **Mobility**
____ I have no problems in walking about
____ I have some problems in walking about
____ I am confined to bed

60. **Self-Care**
____ I have no problems with self-care
____ I have some problems washing or dressing myself
____ I am unable to wash or dress myself

61. **Usual Activities** (*e.g. work, study, housework, family or leisure activities)*
____ I have no problems with performing my usual activities
____ I have some problems with performing my usual activities
____ I am unable to perform my usual activities

62. **Pain/Discomfort**
____ I have no pain or discomfort
____ I have moderate pain or discomfort
____ I have extreme pain or discomfort

63. **Anxiety/Depression**
____ I am not anxious or depressed
____ am moderately anxious or depressed
____ I am extremely anxious or depressed

2.9.3 Appendix C – Informed Consent Form.

AUBURN UNIVERSITY

DEPARTMENT OF INDUSTRIAL
AND SYSTEMS ENGINEERING

(NOTE: DO NOT SIGN THIS DOCUMENT UNLESS AN IRB APPROVAL STAMP WITH CURRENT DATES HAS BEEN APPLIED TO THIS DOCUMENT.)

INFORMED CONSENT
for a Research Study entitled
"The Low Back Cumulative Trauma Index: A Fatigue-Failure Based Risk Assessment Tool"

General Information	You are being asked to take part in a research study. The research study is voluntary, meaning you do not have to take part in it. The procedures, risks, and benefits are fully described in this consent form
Purpose	The purpose of the study is to examine how the work you perform may lead to joint pain, focusing specifically on the low back.
Duration & Visits	The data collection will involve one visit and is expected to take between 1 and 4 hours.
Overview of Procedures	We will attach small sensors to your arms, legs, torso, and head that will help us measure the motions you use to perform your job. You will perform your job as usual and we will collect a 5-10 minute sample of motion for each workstation you work at during your shift. We will also ask you to fill out a questionnaire about any joint pain you might have experienced.
Risks	Risks include potential loss of confidentiality and possible COVID-19 infection (see p. 2).
Benefits	There are no direct benefits to you for participating in this study. The benefits to the researchers is to understand how your body motions and exertions affect development of joint pain.
Alternatives	The alternative is not to participate in the study.

You are invited to participate in a research study to develop a better understand the association between work tasks and low back pain. The study is being conducted under the direction of Sean Gallagher, Professor in the Auburn University Department of Industrial and Systems Engineering. You were selected as a possible participant because you are a healthy individual aged 19-64 years old and meet the following eligibility criteria:

1. You are an employee in a manufacturing facility.
2. You have no history of a physician-diagnosed muscle or bone disease in the low back, neck/shoulder, or upper extremity.
3. You have no history of a physician-diagnosed neurodegenerative disorder that may affect movement (e.g., Parkinson's Disease, multiple sclerosis, etc.)
4. You do not have any health conditions that put you at increase the risk of severe illness from COVID-19 such as cancer, chronic kidney disease, chronic obstructive pulmonary disease, a weakened immune system due to an organ transplant, obesity (body mass index [BMI] of 30 or higher), serious heart conditions, such as heart failure or coronary artery disease, sickle cell disease, or type 2 diabetes mellitus.

Page 1 of 4 **Participant's initials**____

The Auburn University Institutional Review Board has approved this Document for use from 09/14/2020 to 04/08/2021 Protocol # 19-165 EP 1904

AUBURN UNIVERSITY

DEPARTMENT OF INDUSTRIAL AND SYSTEMS ENGINEERING

Risk and Precautions for COVID-19. Due to the need face to face interaction with the researcher or others, there is a risk that you may be exposed to COVID-19 and the possibility that you may contract the virus. For most people, COVID-19 causes only mild or moderate symptoms. For some, especially older adults and people with existing health problems, it can cause more severe illness. Current information suggests that about 1-3% of people who are infected with COVID-19 might die as a result. You will need to review the Information on COVID-19 for Research Participants that is attached to this consent document. To minimize your risk of exposure we will be using screening and rescreening procedures for the researchers, wearing personal protection equipment (masks, safety glasses, gloves and safety shield to reduce chances for transmission, will decontaminate surfaces that researchers or yourself may touch, and use social distance to the fullest extent possible. You will need to follow any precautions or procedures outlined by Auburn University and [redacted].

If you decide to participate in this study, you will be asked to:

1. Complete an eligibility questionnaire to determine if it would be safe to participate in the study.
2. Complete a survey that will ask you some questions about yourself and any aches and pains that you may be experiencing currently or that you've experienced during the last year. This questionnaire may take 30-45 minutes to fill out. *Your answers on this questionnaire will remain confidential. You will be identified only by a code. Only members of the research team will view the survey.*
3. Members of the research team will watch (and videotape) your job in order to assess the number of reaches, lifts, and other motions are required. *The research team will not be judging how well you do your job, but simply want to understand the motions required.*
4. Wear 17 small wearable sensors that will track your motions as you work. This motion data will be examined to see whether they are associated with the pain or injury development.
5. After putting on the sensors, you will perform a few short body movements to calibrate the sensors. Then you will perform your regular job while wearing the sensors. You may be wearing these sensors for a relatively short time (5-10 minutes) or a longer time (perhaps several hours), depending how complex the job is.
6. At the conclusion of the data collection, a research assistant will help you to remove the sensors. Once the sensors are removed your participation in the study will be considered complete.

Your total time commitment related to participation in this study is expected to be approximately 1 to 4 hours total but could be longer for more complex jobs.

Are there any benefits to yourself or others? No direct benefits are anticipated for participants. Benefits to the general population are expected to be: (1) demonstration that real-time low back risk exposure assessment can be successfully collected via wearable sensors; (2)

Participant's initials____

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to show that this data can be used to estimate the daily cumulative load associated with work tasks; (3) to demonstrate that low back loading estimates based on wearable sensors have an association with various low back outcomes (e.g., pain, discomfort, injury).

What are the risks associated with this study? Risks associated with participation in this study would not be expected to exceed those associated with the normal risks in your everyday job. Other than completing epidemiological surveys and donning the wearable sensors, you will be performing your normal work tasks. There is a chance that some chafing and discomfort may be associated with the straps used to secure the wearable sensors, but these risks would be expected to be minor in nature. Other risks, also likely to be minor, would include the chance that participants experience some discomfort or embarrassment when donning or doffing the wearable sensors, or frustration with completing the epidemiology surveys. There is minimal risk that the confidentiality of data obtained in this study would be breached.

Will you receive compensation for participating? You will receive your regular wages during participation, but no additional compensation.

Are there any costs? There will be no costs to you should you agree to participate in this study.

In case of injury, will medical expenses be funded? The likelihood of an injury due to participating in this study is very small. The investigators do not have plans to provide any funds for any medical costs you might incur.

What is the total time commitment? The data collection should only take approximately 1-4 hours, unless your job is very complex. It is possible, but not likely, that data collection might be delayed due to technical difficulties, which might increase the data collection time.

What should I be wearing? There is no particular clothing that you need to wear to participate in the study.

Photographs and Digital Images. With your permission, digital photographs and videotape will be taken of you while you perform your regular work-related tasks. A photo release form will be used to obtain your permission. The images may be used in published materials to help describe the study and for data analysis purposes.

If you change your mind about participating, you can withdraw at any time during the study. Your participation is completely voluntary. If you choose to withdraw, your data can be withdrawn as long as it is identifiable.

Your privacy will be protected. Any information obtained in connection with this study will remain confidential. At the end of the study all links to identifiable information will be destroyed. Information obtained through your participation may be published in a professional journal and/or presented at a professional meeting.

Participant's initials____

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If you have questions about this study, *please ask them now or* contact Associate Professor Sean Gallagher at (334) 734-2955 (seangallagher@auburn.edu). A copy of this document will be given to you to keep.

If you have questions about your rights as a research participant, you may contact the Auburn University Office of Human Subjects Research or the Institutional Review Board by phone (334)-844-5966 or e-mail at hsubjec@auburn.edu or IRBChair@auburn.edu.

HAVING READ THE INFORMATION PROVIDED, YOU MUST DECIDE WHETHER OR NOT YOU WISH TO PARTICIPATE IN THIS RESEARCH STUDY. YOUR SIGNATURE INDICATES YOUR WILLINGNESS TO PARTICIPATE.

Participant's signature	Date	Investigator obtaining consent	Date
Printed Name		Printed Name	

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Page 4 of 4 **Participant's initials____**

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PHOTO RELEASE

During your participation in the research study "The Low Back Cumulative Trauma Index: A Fatigue Failure-Based Risk Assessment Tool", you may be photographed or videotaped. Your signature on the Informed Consent Form gives us permission to do so.

Your signature on this document gives us permission to use the photographs for the additional purpose of publishing the images in a journal article, presentation, or other form of project-related dissemination material beyond the immediate needs of this study. These photographs will not be destroyed at the end of this research, but will be retained indefinitely.

Your permission:

I verify that I am of legal age in my state and give my permission for photographs produced in the study, "The Low Back Cumulative Trauma Index: A Fatigue Failure-Based Risk Assessment Tool" to be used for the purposes listed above, and also to be retained indefinitely.

Participant's Signature   Date

Investigator's Signature   Date

Participant's Printed Name

Investigator's Printed Name

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Page 1 of 1   Participant's initials____

The Low Back Cumulative Trauma Index:
A Fatigue-Failure Based Risk Assessment Tool

Eligibility Questionnaire

Questions to ascertain eligibility for the study:

What is your current age?____________ (Must be aged 19-64 to qualify)

Have you ever had physician-diagnosed muscle or bone diseases in the low back, neck, shoulder, or upper extremity (carpal tunnel syndrome, rotator cuff tear, etc.)?

____Yes ____No (Disqualify if positive)

Have you ever had physician-diagnosed neurodegenerative disease (Parkinson's disease, fibromyalgia, multiple sclerosis, etc.)?

____Yes ____No (Disqualify if positive)

Do you currently have any of the following diseases: cancer, chronic kidney disease, COPD (chronic obstructive pulmonary disease), a weakened immune system due to an organ transplant, obesity (body mass index [BMI] of 30 or higher, serious heart conditions (such as heart failure or coronary artery disease), sickle cell disease, or type 2 diabetes mellitus?

____Yes ____No (Disqualify if any positive)

If eligible, please provide the following information:

Last Name________________________First Name____________________M.I.____________

Address____

City______________________State_______________Zip Code ____________________

Primary Phone Number____________________________

Secondary Phone Number ___________________________

Email address:________________@______________________________

Height (inches)____________Weight (lbs.) ____________________

Participant Prescreening Questions (Day prior to planned testing)

Today's Date: ____________ Participant Code: ____________

Screening Questions	Circle Prospective Participant's Response	
1. Have you experienced any of the following symptoms in the past 48 hours: • fever or chills • cough • shortness of breath or difficulty breathing • fatigue • muscle or body aches • headache • new loss of taste or smell • sore throat • congestion or runny nose • nausea or vomiting • diarrhea	YES	NO
2. Within the past 14 days, have you been in close physical contact (6 feet or closer for at least 15 minutes) with a person who is known to have laboratory-confirmed COVID-19 or with anyone who has any symptoms consistent with COVID-19?	YES	NO
3. Are you isolating or quarantining because you may have been exposed to a person with COVID-19 or are worried that you may be sick with COVID-19?	YES	NO
4. Are you currently waiting on the results of a COVID-19 test?	YES	NO

Any affirmative response will result in cancellation of the scheduled research participation. If all answers are negative, planned research participation may proceed (barring any positive result from screening on the day of the test).

Information on COVID-19 For Research Participants

Auburn University recognizes the essential role of research participants in the advancement of science and innovation for our university, community, state, nation, and beyond. Therefore, protection of those who volunteer to participate in Auburn University research is of utmost importance to our institution.

As you are likely aware, COVID-19 references the Coronavirus that is being spread around the world including in our country, state, and community. *It is important that we provide you with basic information about COVID-19 and the risks associated with the virus so that you can determine if you wish to participate or continue your participation in human research.*

How is COVID-19 spread? COVID-19 is a respiratory virus that is spread by respiratory droplets, mainly from person-to person. This can happen between people who are in close contact with one another. It is also possible that a person can get COVID-19 by touching a surface or object (such as a doorknob or counter surface) that has the virus on it, then touching their mouth, nose, or eyes.

Can COVID-19 be prevented? Although there is no guarantee that infection from COVID-19 can be prevented and no vaccine is currently available, there are ways to minimize the risk of exposure to the virus. Examples include but are not limited to, "social distancing" where individuals physically distance themselves from others (a minimum of 6 feet is often used as a standard distance); using effective barriers between persons; wearing personal protective equipment like masks, gloves, etc.; washing hands with soap and water or sanitizing hands after touching objects; disinfecting objects touched by multiple individuals, etc.

What are the risks of COVID-19? For most people, COVID-19 causes only mild or moderate symptoms, such as fever and cough. For some, especially older adults and people with existing health problems, it can cause more severe illness. While everyone is still learning about this virus, current information suggests that about 1-3% of people who are infected with COVID-19 might die as a result.

Who is most at risk? Individuals over age 65 and those with chronic conditions such as cancer, diabetes, heart or lung or liver disease, severe obesity, and conditions that cause a person to be immunocompromised have the highest rates of severe disease and serious complications from infection.

What precautions should be taken? Based on the proposed research, precautions for the risk of COVID-19 will be addressed on a project by project basis. You will be provided with information about precautions for the project in which you may participate. Any site where research activities will occur that are not a part of Auburn University (offsite location) are expected to have standard procedures for addressing the risk of COVID-19. It is important for participants to follow any precautions or procedures outlined by Auburn University and, when applicable, offsite locations. Further, participants will need to determine how best to address the risk of COVID-19 when traveling to and from research locations. The US Center for Disease Control and Prevention has issued recommendations on types of prevention measures you can use to reduce your risk of exposure and the spread of COVID-19.

Auburn University is continuing to monitor the latest information on COVID-19 to protect our students, employees, visitors, and community. Our research study teams will update participants as appropriate. *If you have specific questions or concerns about COVID-19 or your participation in research, please talk with your study team.* The name and contact information for the study team leader, along with contact information for the Auburn University Institutional Review Board for Protection of Human Research Participants, can be found in the consent document provided to you by the study team.

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2.9.4 Appendix D – Anthropometric Data Form.

Subject ID: Date:

Time:

Measurement	Posture	Reading (Metric units)
Body Weight	Standing	
Body Height	Standing	
Shoe Length	Sitting	
Shoulder Height	Standing	
Shoulder Width	Sitting	
Arm Span	Standing	
Hip Height	Standing	
Hip Width (ASIS)	Standing	
Knee Height	Sitting	
Ankle Height	Sitting	
Pelvis Height*	Standing	
Elbow Width *	Sitting	
Knee Width *	Sitting	
Ankle Width *	Sitting	
Hand Thickness *	Sitting	

* Additional Inputs.

Additional comments:

2.9.5 Appendix E – Data Tracker

Date: ________________ Employee ID: ______________ Subject ID: _________

Evaluation of a Wireless Sensor System for Assessing Cumulative Lumbar Loads in Occupational Settings	Industrial and Systems Engineering Department Auburn University 3301 Shelby Center Auburn, AL 36849 Tel: (334) 844-4340
This form is to be used for: Data Tracking Purposes	

Line-Station Number: ________________ Job Number: _________________ Sex: ______

Job Description: ________________________________ Shift: _______

Part/Tool Name	Part/Tool Weight	Vehicle Model	Part/Tool Descriptions

Date: ________________ Employee ID: _______________ Subject ID: _________

Overall Assignment/Job:

Job Cycle Time: _____ **min** _______ **sec** **OR** ___ **N/A** (no fundamental assignment cycle time)

Sub Task 1:	WPE		OPE	

___**per cycle** ___**intermittent[** _____ **min** ______ **sec]** ___**infrequent[**____ **hr** _____ **min]** ___**atypical**

Comments:

Sub Task 2:	WPE		OPE	

___**per cycle** ___**intermittent[** _____ **min** ______ **sec]** ___**infrequent[**____ **hr** _____ **min]** ___**atypical**

Comments:

Sub Task 3:	WPE		OPE	

___**per cycle** ___**intermittent[** _____ **min** ______ **sec]** ___**infrequent[**____ **hr** _____ **min]** ___**atypical**

Comments:

Sub Task 4:	WPE		OPE	

___**per cycle** ___**intermittent[** _____ **min** ______ **sec]** ___**infrequent[**____ **hr** _____ **min]** ___**atypical**

Comments:

Sub Task 5:	WPE		OPE	

___**per cycle** ___**intermittent[** _____ **min** ______ **sec]** ___**infrequent[**____ **hr** _____ **min]** ___**atypical**

Comments:

Date: ________________ Employee ID: ______________ Subject ID: _________

Overall Assignment/Job:

Job Cycle Time: _____ **min** _______ **sec** **OR** ___ **N/A** (no fundamental assignment cycle time)

Sub Task 6:	WPE		OPE	

___per cycle ___intermittent[_____ min ______ sec] ___infrequent[____ hr _____ min] ___atypical

Comments:

Sub Task 7:	WPE		OPE	

___per cycle ___intermittent[_____ min ______ sec] ___infrequent[____ hr _____ min] ___atypical

Comments:

Sub Task _____:	WPE		OPE	

___per cycle ___intermittent[_____ min ______ sec] ___infrequent[____ hr _____ min] ___atypical

Comments:

Sub Task _____:	WPE		OPE	

___per cycle ___intermittent[_____ min ______ sec] ___infrequent[____ hr _____ min] ___atypical

Comments:

Sub Task _____:	WPE		OPE	

___per cycle ___intermittent[_____ min ______ sec] ___infrequent[____ hr _____ min] ___atypical

Comments:

Date: ________________ Employee ID: ______________ Subject ID: _________

Overall Assignment/Job:

Job Cycle Time: _____ **min** _______ **sec** **OR** ___ **N/A** (no fundamental assignment cycle time)

Sub Task _____:	WPE		OPE	

___**per cycle** ___**intermittent[** _____ **min** ______ **sec]** ___**infrequent[**____ **hr** _____ **min]** ___**atypical**

Comments:

Sub Task _____:	WPE		OPE	

___**per cycle** ___**intermittent[** _____ **min** ______ **sec]** ___**infrequent[**____ **hr** _____ **min]** ___**atypical**

Comments:

Sub Task _____:	WPE		OPE	

___**per cycle** ___**intermittent[** _____ **min** ______ **sec]** ___**infrequent[**____ **hr** _____ **min]** ___**atypical**

Comments:

Sub Task _____:	WPE		OPE	

___**per cycle** ___**intermittent[** _____ **min** ______ **sec]** ___**infrequent[**____ **hr** _____ **min]** ___**atypical**

Comments:

Sub Task _____:	WPE		OPE	

___**per cycle** ___**intermittent[** _____ **min** ______ **sec]** ___**infrequent[**____ **hr** _____ **min]** ___**atypical**

Comments:

Date: ________________ Employee ID: _______________ Subject ID: _________

Definitions

Job- Set of subtasks completed at a given station for each vehicle passing through the given station (subtasks and number may vary between vehicles)

Sub Task- A discrete action or set of actions that is a subset of the normal work cycle ex. Placing and tightening a fastener, lifting part into place

Job Cycle Time- Length of time given to complete all subtasks in a job

Intermittent- subtasks that do not occur every cycle ex. Filling parts containers every 10 cycles; special edition vehicles (trim, tires/rims)

Infrequent- subtasks that do not occur within the normal cycle time, less often than intermittent ex. Weekly cleaning of work space,

Atypical Task- tasks that are not a part of the normal cycle example: clean up or unanticipated maintenance or unplanned event

WPE (Worker Perceived Exertion) – Use Omni-Res Scale, have worker pick closest whole number for each subtask

OPE (Observer Perceived Exertion) – Auburn University Observer. Use Omni-Res Scale for each sub task. Observer pick closest whole number

Date: ________________ Employee ID: ______________ Subject ID: _________

The Shoulder Tool

Sub Task #	**Task Name**	**Shoulder R/L/Both** (Circle One)	**Push/Pull/Load Handling** (Circle One)	**Lever Arm (Inch)**	**Load (lbs)**	**Comments** 1L 1R
		L R Both	Load/Lift V. Push/Pull Down↓ V. Push/Pull Up ↑ H. Push/Pull →			
		L R Both	Load/Lift V. Push/Pull Down↓ V. Push/Pull Up ↑ H. Push/Pull →			
		L R Both	Load/Lift V. Push/Pull Down↓ V. Push/Pull Up ↑ H. Push/Pull →			
		L R Both	Load/Lift V. Push/Pull Down↓ V. Push/Pull Up ↑ H. Push/Pull →			
		L R Both	Load/Lift V. Push/Pull Down↓ V. Push/Pull Up ↑ H. Push/Pull →			
		L R Both	Load/Lift V. Push/Pull Down↓ V. Push/Pull Up ↑ H. Push/Pull →			
		L R Both	Load/Lift V. Push/Pull Down↓ V. Push/Pull Up ↑ H. Push/Pull →			
		L R Both	Load/Lift V. Push/Pull Down↓ V. Push/Pull Up ↑ H. Push/Pull →			
		L R Both	Load/Lift V. Push/Pull Down↓ V. Push/Pull Up ↑ H. Push/Pull →			
		L R Both	Load/Lift V. Push/Pull Down↓ V. Push/Pull Up ↑ H. Push/Pull →			

Date: ________________ Employee ID: ______________ Subject ID: _________

LiFFT

Sub Task #	Task Name	Lever Arm (Inch)	Load (lbs)	Repetitions (per work day)	Comments

Date: ________________ Employee ID: ______________ Subject ID: _________
DUET

Sub Task #	Task Name	OMNI-RES (write number)	Repetitions	Comments

OMNI RES Scale
0: Extremely Easy
1
2: Easy
3
4: Somewhat Easy
5
6: Somewhat Hard
7
8: Hard
9
10: Extremely Hard

2.9.6 Appendix F – Survey Tracker Form

Evaluation of a Wireless Sensor System for Assessing Cumulative Lumbar Loads in Occupational Settings	Industrial and Systems Engineering Department Auburn University 3301 Shelby Center Auburn, AL 36849 Tel: (334) 844-4340
This form is to be used for: Survey Tracking Purposes	

Age (years): ____________________
Sex: ____________________
Employee ID: ____________________
Job Title: ____________________
Shift: ____________________
Line: ____________________
Team: ____________________
Stations: ____
Time working at this facility:
Years: ________ Months: _________ Weeks: ________
Time working on current team:
Years: ________ Months: _________ Weeks: ________

Participating in motion capture session: Yes: ________ No: _________

For Researchers Only (Use calipers and scale with shoes on):
Height (cm): ____________________
Weight (lbs): ____________________

3. Publications

3.1 Conference Presentations

- Nail-Ulloa, I., Gallagher, S., Huangfu, R., Bani-Hani, D., & Pool, N. (2021, September). Validation of a Wireless Sensor System for the Estimation of Cumulative Lumbar Loads in Occupational Settings (Pilot Results). In Proceedings of the Human Factors and Ergonomics Society Annual Meeting (Vol. 65, No. 1, pp. 489-494). Sage CA: Los Angeles, CA: SAGE Publications.

3.2 Symposia

- Nail-Ulloa, I., Gallagher, S., Huangfu, R., Bani-Hani, D., & Pool, N. (2021, October). Validation of a Wireless Sensor System for the Estimation of Cumulative Lumbar Loads in Occupational Settings (Pilot Results), Samuel Ginn College of Engineering, Auburn University.
- Nail-Ulloa, I., Gallagher, S., Huangfu, R., Bani-Hani, D., & Pool, N. (2021, March). Validation of a Wireless Sensor System for the Estimation of Cumulative Lumbar Loads in Occupational Settings (Biomechanical Modeling). Southeast Regional Research Symposium, Deep South Center for Occupational Health and Safety ERC, Central Appalachian Regional ERC, Sunshine ERC, North Carolina Occupational Safety and Health ERC, Southeastern Coastal Center for Agricultural Health and Safety, and Southeast Center for Agricultural Health and Injury Prevention. (Remote Symposium).

3.3 Webinars

- Fatigue failure theory and its relationship with musculoskeletal disorders. Webinar. Chilean Society of Ergonomics, Santiago, Chile. July 13th, 2021.
- An Introduction to ergonomic risk factors, Webinar. Institute of Management and Industry, Universidad Austral de Chile, Puerto Montt, Chile. October 9th, 2020.

3.4 Dissertation/Thesis

- Doctoral Thesis: Validation of a wireless sensor system for the estimation of cumulative lumbar loads in occupational settings. Ph.D. Candidate Ivan Nail Ulloa, Industrial and Systems Engineering, Auburn University. Expected graduation: Fall 2022.

C. PRODUCTS

C.1 PUBLICATIONS **Are there publications or manuscripts accepted for publication in a journal or other publication (e.g., book, one-time publication, monograph) during the reporting period resulting directly from this award?** No
C.2 WEBSITE(S) OR OTHER INTERNET SITE(S) NOTHING TO REPORT
C.3 TECHNOLOGIES OR TECHNIQUES NOTHING TO REPORT
C.4 INVENTIONS, PATENT APPLICATIONS, AND/OR LICENSES **Have inventions, patent applications and/or licenses resulted from the award during the reporting period?** No **If yes, has this information been previously provided to the PHS or to the official responsible for patent matters at the grantee organization?** No
C.5 OTHER PRODUCTS AND RESOURCE SHARING NOTHING TO REPORT

D. PARTICIPANTS

D.1 WHAT INDIVIDUALS HAVE WORKED ON THE PROJECT?

Commons ID	S/K	Name	Degree(s)	Role	Cal	Aca	Sum	Foreign Org	Country	SS
SZG0036	Y	Gallagher, Sean	MS,PHD	PD/PI	1.0	0.0	0.0			NA
GADAVIS	Y	Davis, Gerard A	BS,MS,PHD	PD/PI	1.5	0.0	0.0			NA
SESEK@AUBURN.EDU	N	Sesek, Richard Frank	PHD	Co-Investigator	1.0	0.0	0.0			NA
MSCHALL	N	Schall, Mark Christopher	BS,MS,PHD	Co-Investigator	0.0	0.0	0.8			NA
RONGH24	N	Huangfu, Rong		Postdoctoral Scholar, Fellow, or Other Postdoctoral Position	1.0	0.0	0.0			NA
	N	Nail, Ivan	MISE	Graduate Student (research assistant)	12.0	0.0	0.0			NA
	N	Ma, Yuting	MISE	Graduate Student (research assistant)	8.5	0.0	0.0			NA
	N	Hani, Dania Bani	MISE	Graduate Student (research assistant)	1.0	0.0	0.0			NA

Glossary of acronyms:
S/K - Senior/Key
Cal - Person Months (Calendar)
Aca - Person Months (Academic)
Sum - Person Months (Summer)
Foreign Org - Foreign Organization Affiliation
SS - Supplement Support
RS - Reentry Supplement
DS - Diversity Supplement
OT - Other
NA - Not Applicable

D.2 PERSONNEL UPDATES

D.2.a Level of Effort

Not Applicable

D.2.b New Senior/Key Personnel

Not Applicable

D.2.c Changes in Other Support

Not Applicable

D.2.d New Other Significant Contributors Not Applicable
D.2.e Multi-PI (MPI) Leadership Plan Not Applicable

E. IMPACT

E.1 WHAT IS THE IMPACT ON THE DEVELOPMENT OF HUMAN RESOURCES?
Not Applicable
E.2 WHAT IS THE IMPACT ON PHYSICAL, INSTITUTIONAL, OR INFORMATION RESOURCES THAT FORM INFRASTRUCTURE?
NOTHING TO REPORT
E.3 WHAT IS THE IMPACT ON TECHNOLOGY TRANSFER?
Not Applicable
E.4 WHAT DOLLAR AMOUNT OF THE AWARD'S BUDGET IS BEING SPENT IN FOREIGN COUNTRY(IES)?
NOTHING TO REPORT

G. SPECIAL REPORTING REQUIREMENTS SPECIAL REPORTING REQUIREMENTS

G.1 SPECIAL NOTICE OF AWARD TERMS AND FUNDING OPPORTUNITIES ANNOUNCEMENT REPORTING REQUIREMENTS

NOTHING TO REPORT

G.2 RESPONSIBLE CONDUCT OF RESEARCH

Not Applicable

G.3 MENTOR'S REPORT OR SPONSOR COMMENTS

Not Applicable

G.4 HUMAN SUBJECTS

G.4.a Does the project involve human subjects?

Not Applicable

G.4.b Inclusion Enrollment Data

NOTHING TO REPORT

G.4.c ClinicalTrials.gov

Does this project include one or more applicable clinical trials that must be registered in ClinicalTrials.gov under FDAAA?

G.5 HUMAN SUBJECTS EDUCATION REQUIREMENT

NOT APPLICABLE

G.6 HUMAN EMBRYONIC STEM CELLS (HESCS)

Does this project involve human embryonic stem cells (only hESC lines listed as approved in the NIH Registry may be used in NIH funded research)?

No

G.7 VERTEBRATE ANIMALS

Not Applicable

G.8 PROJECT/PERFORMANCE SITES

Not Applicable

G.9 FOREIGN COMPONENT

No foreign component

G.10 ESTIMATED UNOBLIGATED BALANCE

Not Applicable

G.11 PROGRAM INCOME

Not Applicable

G.12 F&A COSTS

Not Applicable

I. OUTCOMES

I.1 What were the outcomes of the award?

The results of this research may lead to several improvements in occupational health and safety. One of the main findings is that fatigue failure methods can be used to evaluate the risk of musculoskeletal disorder development. One benefit to this is that a number of techniques and methods are available to help assess the cumulative loading experienced by workers that may lead to MSD development. It has been believed by many in the field that MSDs are the result of the cumulative load experienced by workers; however, the methods developed for cumulative damage assessment have been based on rather scant evidence. On the other hand, fatigue failure theory has established, validated methods of assessing the effect of cumulative loading on materials, even for highly variable loading conditions (spectrum loading). This spectrum loading is commonly experienced by human beings (including in occupational settings), and having validated methods of assessing the cumulative effect of spectrum loading is believed to be of significant value in terms of MSD risk assessment. Results of this study suggest that these methods are associated with low back pain outcomes (historical data on back injuries and current low back pain survey data). Currently many methods of assessing continuous loading are being developed (using video and inertial measurement devices). The techniques evaluated here may be able to assess the cumulative load associated with such continuous loading data measurement systems.