FUSE TECHNICAL REPORT

STRONGARM TECH

Contents

Introduction

StrongArm Technologies is committed to conducting industry-leading safety data analyses that meet the rigorous expectations of the scientific community and the ergonomics industry. As such, StrongArm has consulted with leading independent ergonomics experts to develop a fully research-backed and validated system with the FUSE Risk Management Platform. All aspects of the FUSE Platform, including scientific models, analysis algorithms, and data collection methods have been developed and tested in consultation with these experts.

This document highlights several major validation tests conducted on the FUSE hardware, along with explanations of the lower-back disorder (LBD) risk model utilized in the platform. Additionally, this paper details StrongArm's algorithmic implementation of the risk model, and ergonomics testing conducted in collaboration with The Ergonomics Center of North Carolina State University to validate the FUSE Risk Score outputs. Test results indicate typical FUSE device accuracies are within 3.0 degrees positional and 2.5

degrees per second velocity when using the 3-Point strap. Additionally, FUSE Risk Score output testing indicates agreement between the FUSE and industry standard LBD evaluation device to within 2.0 percentage points of LBD risk probability estimation when comparing the relative risks of lifting tasks.

FUSE Accuracy Validation Testing

Device

The FUSE Risk Management Platform consists of a FUSE device and software analysis system for evaluating risk factors in the workplace, including risk of lower-back disorders. To evaluate LBD risk, the FUSE device is placed on the user's chest through adjustable soft-goods straps to measure the orientation of the user's trunk over time. With this arrangement, trunk position in the user's sagittal, lateral, and twisting directions can be fully determined, along with trunk movement velocity. These parameters are then processed for determining LBD risk as described in later sections.

Figure 1. FUSE device off-body

Figure 2. FUSE device worn with 3-Point strap

The FUSE device contains a 9 degrees of freedom Inertial Measurement Unit (IMU) chip for determining these body trunk movements. This chip incorporates a 3-axis accelerometer, gyroscope, and magnetometer, which combine to produce accurate spatial readings of the unit in any orientation. Such sensor technology has been specifically developed for applications such as the FUSE device, which require accurate orientations in space. When calibrated from the factory, the IMU delivers angular velocity accuracy within 1/10th a degree per second, and acceleration accuracy within 1/1000th a G(gravitational constant, 9.8 m/s^2).[6]

Testing Apparatus

A dynamic testing fixture has been developed to confirm the accuracy of the FUSE device's IMU readings when placed onto a human body using the strap attachment methods. The dynamic testing fixture simulates and compares human trunk motions to FUSE data outputs. The fixture consists of a simulated human torso attached to a rotating platform supported by a hinged bend axis. An Omron E6B2-C rotary encoder[5] attaches to the end of the hinged axis using a shaft coupling. With this arrangement, any planar motions encountered by the torso are subsequently recorded by the rotary encoder. The rotating platform can also be locked in place prior to testing to ensure all motions are entirely in either the sagittal or lateral plane. See figures 3-5 below for the three planar motions as exhibited by the testing fixture.

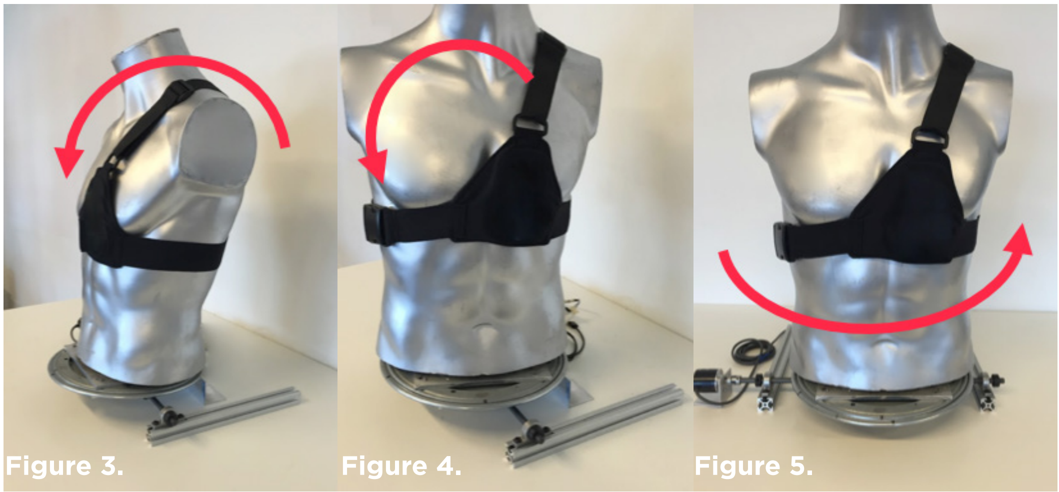

Figure 3. Sagittal Bending

Figure 4. Lateral Bending

Figure 5. Twisting

Testing Method

The FUSE readings were recorded in conditions similar to when worn on Industrial Athletes, and allow for direct comparison between devices and the encoder. Tests were conducted by moving the torso through a series of 10 bends for each of the 3 primary planes - sagittal, lateral, and twisting. Both the 3-Point strap and the FLx™ attachment strap were tested simultaneously for each test to directly validate the accuracy of the FUSE device on all available attachment methods. Applied motions to the simulated trunk were also recorded with the Omron E6B2-C rotary encoder at a resolution of 0.1 degrees for the sagittal and lateral tests, allowing for comparison between results from the FUSE devices on both attachment methods. Twist tests were analyzed for comparison between FUSE devices on both attachment methods since the hinged encoder axis was fixed for these tests. For each bend, the maximum positional and velocity values are recorded for both the encoder and the devices.

FUSE Accuracy

Results of the 10 trials for both position and velocity agreement have been averaged and tabulated below. Deviations are calculated as the difference between FUSE device reading for each attachment method and the rotary encoder. Deviations between attachments are taken as the difference between FLx™ attachment and 3-Point strap reading.

Test results indicate that the FUSE device records body angular position to within 2.7 degrees of measured encoder values when worn with the 3-Point strap, with body angular velocities consistent within 2.2 degrees per second of the encoder. Positional and velocity accuracy of the FLx™ attachment were also highly consistent at 5.5 degrees and under 1.0 degrees per second respectively.

Additionally, the 3-Point strap and FLx™ attachment readings are shown to be highly consistent with each other, with all averages within 6.1 degrees of each other for positional readings and 2.8 degrees per second for velocity readings. An interesting note is the tendency for FLx™ attachment readings to consistently estimate a slightly higher value than the 3-Point strap for both position and velocity. This is likely an effect of the differing attachment points for both fixture methods. Due to the chest-strap positioning across the user's chest, the FLx™ shoulder straps can introduce slightly more movement into the FUSE system than the 3-Point strap.

These slight differences should be taken into context of the overall accuracy, however, which still delivers consistent performance within 5.5 degrees of encoder readings. In particular, when compared to common alternatives in the workplace of visual and video analysis, the FUSE device performance ranks highly for measuring worker trunk movements. Overall, these tests highlight the reliability of both FUSE attachment methods for recording trunk positions and velocities in dynamic movements.

SAGITAL	ENCODER	FUSE - 3-POINT STRAP	FUSE - FLX™ ATTACHMENT	DEV. 3-POINT -ENCODER	DEV. FLX™ -ENCODER
Max Position [degrees]	43.7	45.6	47.0	1.9	3.3
Max Velocity [degrees/sec]	34.7	32.8	35.6	-1.9	0.9

Table 1. Sagittal movement test comparisons

LATERAL	ENCODER	FUSE - 3-POINT STRAP	FUSE - FLX™ ATTACHMENT	DEV. 3-POINT -ENCODER	DEV. FLX™ -ENCODER
Max Position [degrees]	29.2	31.9	34.7	2.7	5.5
Max Velocity [degrees/sec]	27.9	25.7	27.5	-2.2	-0.4

Table 2. Lateral movement test comparisons

TWIST	FUSE - 3-POINT STRAP	FUSE - FLX™ ATTACHMENT	DEV. FLX™ - 3-POINT
Max Position [degrees]	29.2	31.9	34.7
Max Velocity [degrees/ sec]	35.9	35.0	-0.9

Table 3. Twist movement test comparisons

LBD Risk Score Model Details

The FUSE device and data analysis package collects and interprets a large amount of body movement data that can be evaluated in many different ways. To make actionable decisions clearer to users, the FUSE reports a Safety Score that uses decades of scientifically-backed research to condense many aspects of this information into a single value. This single Safety Score value has been proven to directly correspond to the risk of lower back disorder. Thus the Safety Score provides an easy method for interpreting the risk of various trunk movements, and the effect of interventions on LBD risk level.

Scientific Backing

Extensive research conducted by Marras et al.[3] at Ohio State University's Institute for Ergonomics form the scientific basis for the StrongArm Safety Score. During these studies, participants wore a device that measured the lumbar spine motion characteristics while performing manual material handling job tasks. Over 400 jobs were evaluated across a range of industries. These data were then collected, and compared against historical lower back disorder data for all companies participating. In this manner, it was possible to associate lower back disorder risk with dynamic trunk motion characteristics of workers on the job, hence the Risk Score.

A following study conducted by Marras et al.[4] using the same technology validated the predictive nature of this risk model. Over a period of time, the Risk Score was tracked for various workers - some who underwent an ergonomic intervention and some who did not. After the observation period, the lower back disorder incidence rates were compared to the Risk Score, leading to statistically significant results that correlated a change in Risk Score directly to a change in injury incidence rate.

The FUSE platform uses this Risk Score in its inverse to create the Safety Score. In other words, a high Risk Score and high risk of LBD corresponds to a low Safety Score, and vice versa. Numerically, a 70% Risk Score corresponds to a 30% Safety Score. In this manner, Safety Score is used in the same context as the original research - to indicate higher or lower levels of lower back disorder risk.

FUSE Accuracy

From the scientific research of the above studies, lower back risk can most accurately be predicted using 5 key trunk motion characteristics. While many other body motion characteristics are important, the research suggests that all other influencing factors of injury are encompassed by these 5 key factors due to the dynamic nature of the movements. Thus adding other factors to the Risk Score determination would not make the Risk Score more accurate.[3] The included factors are as follows:

Maximum Sagittal Flexion Angle: Measures the angle of forward spine flexion in the sagittal plane. Taken as the maximum value for a given lift or period of lifts.

Maximum Moment: Determined as package weight multiplied by the horizontal distance between the center of the hands where the load is being held and the L5/S1 joint in the lower spine.

Average Twist Velocity (ATV): Measures the average velocity of movement in the transverse, or axial plane while lifting. Taken as an average for a given lift or period of lifts.

Lift Rate: Describes the total number of packages or objects handled in a given time period. Measured in lifts per hour. Lifts are defined as completing one job task in a manual material handling setting.

Maximum Lateral Velocity (MLV): Measures the maximum velocity of movement in the lateral, or frontal plane. Taken as the maximum value for a given lift or period of lifts.

When wearing the FUSE, these 5 factors are collected, and weighed in a logistic regression equation as determined by the academic research to yield a Risk Score, and thus, Safety Score.

FUSE Risk Score Implementation Details

Given the novel nature of the FUSE data sensing technology, collected measurements from the device undergo a data processing algorithm to interpret the results correctly. Major algorithm parameters that affect Safety Score results have also been tested for accuracy and functionality. Constants relating to the human body are determined from established anthropometric medical research.

Calibration

To address the unique positioning of the FUSE sensor on each user's body, every data file undergoes a calibration algorithm to ensure trunk motion readings are relative to the user's natural standing position. For each data file, the IMU angle readings in each of the 3 planes which occur for the longest length of time are selected as the neutral positions. All IMU raw readings are then translated based off this zeroed position, allowing all angle readings presented to be relative to the user's natural resting position while standing.

Lift Detection

Lifting in a manual material handling setting typically involves some forward bending, creating "peaks" in the sagittal flexion movement data. Using this occurrence, lifts are determined by the FUSE using a peak detection algorithm that can identify high points in movement data. Whenever a peak occurs, the algorithm identifies that specific movement curve as a lift, and records the high points of the trunk motion characteristics. An in-house study has been conducted validate the algorithm's accuracy at detecting lifts. A controlled test environment was established with varying table heights and package sizes. Packages ranged between 10 and 20 pounds, while lifting scenarios included ground to table, table to ground, table to table, and lift to carry situations to give a range of possible lifting experiences seen in the workplace. A study group of 6 test participants were instructed to move these packages across the test course, each conducting a total of 40 lifts each during the trial. Algorithm lift detection parameters were then optimized to best match the actual number of lifts performed. Results of this optimization resulted in an average accuracy within 5% of the true number of lifts performed across all participants.

Load Moment Details

Due to the FUSE's use in dynamic workplace setting, exact measurement data for the weight of items lifted at any given time is not available. To address this, specific job functions can be assigned average package weights within the FUSE platform. For all lifts occurring without average package weight data input, the algorithm assumes a constant average package weight of 14.5lbs. All lifts are assumed to be at a horizontal distance of 12 inches from where the load is held in the center of the hands to the L5/S1 joint in the lower spine. Both values are representative of manual material handling tasks and lifting characteristics, and can be adjusted as necessary for a specific application.

Trunk Motions Details

The original research that developed the Risk Score measured trunk motion data by measuring change in the lumbar section of the spine, using a device called the Lumbar Motion Monitor[2] described in a later section. For purposes of mobility and user experience, the FUSE device measures trunk motions on the chest. To maintain the relatability between the two measurement methods, a geometrical constant is applied to all trunk motion variable values. This accounts for the extensive curvature of the human spine when performing a dynamic lift by relating lumbar spine length to FUSE position above the hip. Established research data cataloged by Coutsoukis1 presents lumbar spine lengths for both males and females. To determine average FUSE position, a range of male and female users in their comfortable worn position have been measured to determine average positioning of the FUSE relative to the L5/S1 region for both the 3-Point attachment straps and the FLx™ attachment. With this data, the FUSE readings can be directly translated into values inputted into the Risk Score equation. All velocities undergo filtering to eliminate noise inherent in on-body motion sensing.

FUSE Risk Score Validation Testing

Testing described previously has shown the accuracy of the FUSE at measuring trunk motion characteristics. To further solidify the legitimacy of the FUSE Risk Score calculations, a study has also been conducted in partnership with The Ergonomics Center of North Carolina State University (NCSU) to validate the system's algorithmic implementation of the LBD risk model.

Device

In this test, the measurement tool originally used to develop the LBD risk model, called the Lumbar Motion Monitor (LMM), developed by Marras et al.[2] was used as a basis of comparison for the FUSE device. This measurement tool attaches to the back of participant using a series of hook and loop straps, and consists of a lower and upper unit. This device measures the dynamic motions of the user's lumbar spine during lifting tasks, and was used in the development of the original Risk Score model.[3] During usage, the device operator manually identifies periods when lifting are occurring, and marks those times in the analysis program in real-time. See figures 4 and 5 below for images of the LMM as fitted onto a test participant prior to testing.

The LMM was calibrated, fitted, and operated by a professionally trained ergonomist from The Ergonomics Center of NCSU during all tests to ensure proper usage of the device and software.

Figure 6. LMM on participant's back

Figure 7. LMM attachment straps on-body

Testing Method

Both the LMM and the FUSE device were worn simultaneously while conducting a wide range of lifting scenarios. These scenarios included pallet to pallet, ground to high table, pallet to waist-high table, and waist-high table to high table arrangements. For each of the scenarios, 20 lifts were performed. Half of the lifts were performed with behavior deemed by ergonomist experts as low risk behavior that involved predominantly pivot stepping and "lifting with the legs", with the other half incorporating high risk motions including twisting of the trunk and rapid trunk movement. Three participants were included in the study, and two FUSE devices were used for each test. A trained ergonomist operated the LMM software during all tests to properly identify periods of lifting and record them in the analysis.

Results of these tests allow the relative change in Risk Score from the LMM output between high and low risk tests to be compared to the FUSE outputs. Each participant naturally moved in a slightly different manner, and changed behavior between the high and low risk tests to different degrees. Thus in the context of how Risk Scores are evaluated, correctly identifying the relative risk difference between movement patterns in different scenarios and over time is the key comparison metric to confirm functionality. As such, the average difference between high and low risk testing has been presented.

FUSE Accuracy

Results from the LMM-FUSE testing comparison can be found below in Table 4. Deviations are taken as the average difference between FUSE Risk Score change and LMM Risk Score change between high and low risk tests. Differences are averaged across the 4 tests for each participant, each of which had an identical number of lifts performed per each test. Values are presented as percentage points indicating probability of high-risk group membership, as detailed in Marras et al.[3] Note that variations exist between participants due to differences in natural motion characteristics exhibited during high and low risk lifting, specific to each individual.

These test results indicate remarkably close agreement between FUSE and LMM estimations of changes in Risk Score between motion characteristics. On average, the FUSE system records these changes to less than 1.8 percentage points of the baseline LMM estimation. In other words, the FUSE device and algorithm offer consistent measures of relative risk for individuals between different manual material handling scenarios to those that the original Risk Score model and device would output.

PARTICIPANT	AVG. CHANGE HIGH-LOW RISK - LMM [%]	AVG. CHANGE HIGH-LOW RISK - FUSE A [%]	AVG. CHANGE HIGH-LOW RISK - FUSE B [%]	DEV. FUSE A - LMM [%]	DEV. FUSE B - LMM [%]
Max Position [degrees]	43.7	45.6	47.0	1.9	3.3
Max Velocity [degrees/sec]	34.7	32.8	35.6	-1.9	0.9

Table 4. FUSE-LMM LBD risk model responsiveness comparison

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