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Instrumentation for measuring dynamic spinal load moment exposures in the workplace

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ABSTRACT

Prior research has shown the load moment exposure to be one of the strongest predictors of low back disorder risk in manufacturing jobs. However, to extend these finding to the manual lifting and handling of materials in distribution centers, where the layout of the lifting task changes from one lift to the next and the lifts are highly dynamic, would be very challenging without an automated means of quantifying reach distances and item weights. The purpose of this paper is to describe the development and validation of automated instrumentation, the Moment Exposure Tracking System (METS), designed to capture the dynamic load moment exposures and spine postures used in distribution center jobs. This multiphase process started by obtaining baseline data describing the accuracy of existing manual methods for obtaining moment arms during the observation of dynamic lifting for the purposes of benchmarking the automated system. The process continued with the development and calibration of an ultrasonic system to track hand location and the development of load sensing handles that could be used to assess item weights. The final version of the system yielded an average absolute error in the load's moment arm of 4.1 cm under the conditions of trunk flexion and load asymmetry. This compares well with the average absolute error of 10.9 cm obtained using manual methods of measuring moment arms. With the item mass estimates being within half a kilogram, the instrumentation provides a reliable and valid means for assessing dynamic load moment exposures in dynamic distribution center lifting tasks.

1. Introduction

Studies exploring the relationship between low back disorders (LBD) and occupational lifting (NIOSH, 1997) have identified manual materials handling (MMH) as the most common cause of LBD (Spengler et al., 1986; Bigos et al., 1986). It is estimated that lifting and MMH account for up to 66% of all back injuries (National Research Council and Institute of Medicine, 2001). Moreover, epidemiologic studies have reported that repetitive lifting was indeed a risk factor for LBD (Kelsey et al., 1984; Magora, 1975).

The nature of occupational lifting is changing within the United States. Previously much of the lifting exposure was associated with routine lifting tasks in manufacturing facilities (Marras et al., 1993). However, as more manufacturing is performed outside of the US, there has been a dramatic increase in the number of distribution centers (DCs) used to distribute these foreign made products throughout the country. Hence, the workforce's exposure to frequent lifting will be increasing as automating these distribution MMH tasks appears cost prohibitive and in many cases not feasible with today's technology. Associated with this change there is less exposure of workers to *identical* repetitive lifting tasks. In distribution centers the greater variation in the items handled and temporal spacing between lifts makes the application of existing ergonomic assessment techniques extremely challenging (Waters et al., 1999) and possibly of questionable validity. In large part, this is because current ergonomic assessment techniques have not been developed to accommodate the variation in load magnitudes or the temporal parameters that would describe the duty cycle. Thus, there is a need to develop methods and instrumentation that can accurately quantify the workload encountered in distribution centers.

The underlying assumption of biomechanical reasoning is that risk of injury occurs when the load imposed upon a tissue exceeds the tolerance of a tissue (McGill, 1997). The load moment may be a good surrogate measure of tissue load. This line of thinking is consistent with the NIOSH recommendations for lifting where we can see that the most powerful factor in these assessments is associated with load moment (NIOSH, 1981; Waters et al., 1993). In a study on the predictive power of the load moment, it was found that the load moment produced an odds ratio for high risk vs. low risk of LBD of 4.08 (C.I. 2.62–6.34) using average moment arm distance (horizontal distance) and 5.17 (C.I. 3.19–8.38) when maximum horizontal distance was used to compute moment (Marras et al., 1999). These values were significantly greater than any other single factor considered in the analysis. In summary, the

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literature suggests that load moment knowledge is essential to understanding the load-tolerance relationship of the spine and the subsequent risk of LBD.

Biomechanical studies also suggest that cumulative load exposure metrics may provide a promising measure of LBD risk. Kumar (1990) used a 2-dimensional static model to describe cumulative load in 161 workers and found that those exposed to greater cumulative loading were more apt to report injuries. Combined with the load moment results described above, the temporal patterns of the work including the work and rest period parameters that describe the duty cycle, would likely have a profound effect on the biomechanical loadings experienced by workers in fast-paced distribution center jobs.

In summary, we believe the biomechanical literature suggests that future risk models aimed at describing LBD risk in repetitive MMH distribution center jobs should be based upon load moment exposures both in terms of magnitude and temporal exposure patterns. In order to conduct the detailed epidemiologic investigations that can be used to construct these risk models, accurate and valid instrumentation capable of providing reliable load moment exposures needs to be developed. The purpose of this paper is to describe the multi-phased process by which we developed and validated instrumentation that could be used for characterizing MMH exposures in distribution center workers through load moment and duty cycle parameters. This manuscript describes the research conducted in each phase to ensure we were developing accurate and reliable instrumentation.

2. Methods

2.1. Phase 1: determining the accuracy of conventional moment arm measurements

The purpose of this first phase was to assess the fidelity of the current means of measuring load moment for benchmarking purposes. Historically, load moment has been documented by measuring the horizontal distance of the load from the spine using a tape measure (see Fig. 1) and multiplying this distance by the weight of the load lifted, where the load weight is measured with a scale (Marras et al., 1993, 1995). This type of approach, while feasible in manufacturing environments where the lifting tasks tend to be cyclic and included limited variation, would be very difficult to implement in distribution center environments where the object handled, the lift location and lift configuration change from one lift to the next.

Fig. 1. The traditional approach to measuring load moment entailed multiplying a measurement of the horizontal distance between the base of the spine and the object's center of mass by the weight of the object.

2.1.1. Approach

An experiment was performed in which the moment arm distances measured using the conventional tape measure technique were compared with moment arm measures derived from a magnetic tracking device (Ascension, Burlington, VT) that was capable of monitoring distances in a laboratory setting with a static RMS accuracy of 1.8 mm (Ascension, 2008). A single individual performed the lifting task in which a stack of 8 boxes was individually transferred from one side of the person lifting to the other side. The task was performed twice, first with a person moving stacked boxes from left to right and then moving the stacked boxes from right to left. A total of 16 lifts were observed for each subject. The *dependent measure* consisted of the average absolute error (AAE) indicating the difference between the magnetically derived moment arm distance and the moment arm measured by the data collectors.

2.1.2. Subjects

Four participants were recruited to make moment arm measurements. All had considerable experience measuring moment arms in industrial settings.

2.1.3. Procedure

One of our staff served as the "lifter" for all of the participants. He worked at a pace of approximately 4 lifts per minute that could not be interrupted for measurement. The subjects were asked to assess the maximum horizontal moment arm as they would in industry which they would verbalize so it could be recorded by the investigator.

2.1.4. Results

The results indicated that the average AAE of all data collectors was 10.9 cm with a standard deviation of 5.8 cm. Individual subjects AAE ranged from 7.4 cm to 15.2 cm. Hence, this analysis indicated that traditional measurement methods for assessing moment arms during dynamic lifting include substantial within subject error in addition to the between subject variation. Moreover, these can be used to benchmark specially designed instrumentation aimed at assessing these moment arms in active distribution center jobs.

2.2. Phase 2: developing ultrasound instrumentation for measuring moment arms

Ultrasound technology can measure distance by tracking directional ultra high frequency sound. The technology has been widely used as a focusing mechanism on cameras where ultra high frequency sound is bounced off an object and received by the camera. The time it takes this signal to be emitted from the camera and return is a measure of the distance from the object. This technology has the advantage that the transmitters and receivers are relatively small, light and inexpensive. Thus, multiple transmitters and receivers can be wired together in a system that could triangulate a target, thereby providing information about target distance, height, and orientation.

A prototype system was assembled to test the feasibility of using this type of hardware to track hand locations. The ultrasound receivers were mounted on a backpack frame as were the data acquisition system, accelerometers, and a wearable computer. The ultrasound transmitters used to generate the ultrasound signal (Fig. 2a) were placed at the hands (Fig. 2b) to serve as indicators of the box location. Fig. 2c shows a series of three receivers placed at

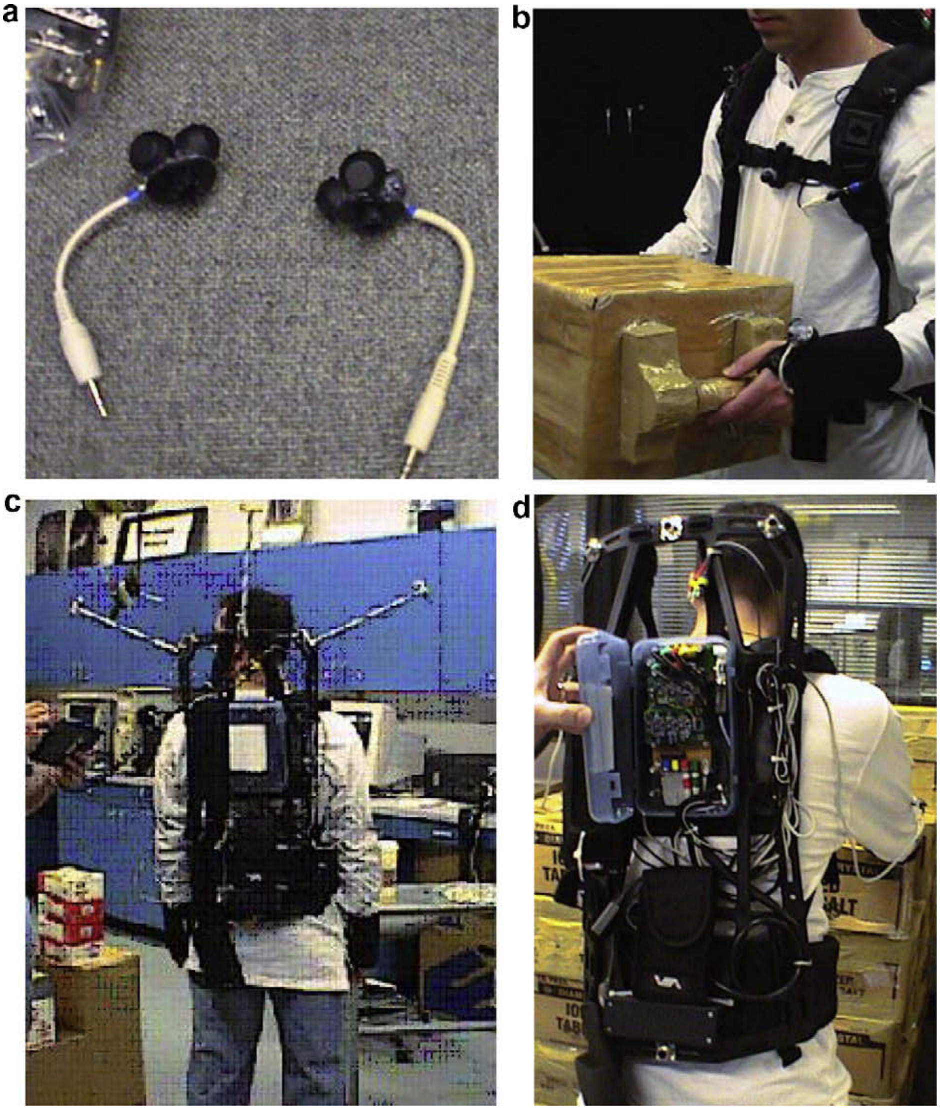

Fig. 2. Sonic (ultrasound) receiver cluster (a), sonic transmitters mounted on the subject's hands and receivers visible on the backpack belts (b), backpack hardware system with receivers protruding from the backpack frame (c), and a close up view system electronics including the DAQ board, accelerometer (black box at base of backpack), and wearable computer (black pouch) (d). The prototype system weighed nearly 17 kg.

the ends of flexible springs attached to the backpack frame. A three dimensional accelerometer, mounted to the backpack frame, allowed the back's orientation relative to the world and acceleration data to be monitored. This prototype system was designed such that the data could be transmitted via a wireless network or stored on a flash card for later download. The initial version of the entire backpack system weighed 17 kg.

The system logic was designed so that ultrasonic "pulses" were generated from the hand transmitters at regular intervals (20 kHz). The receivers placed at various locations on the backpack frame and backpack straps sampled the reception of the transmitted signal in a set sequence. The system was capable of differentiating the timing between receptions at the various receivers, thereby determining the linear distance of the transmitter from the receiver. The system's software used the linear distance information from the various receivers to "triangulate" the target. The torso flexion, which was calculated based upon data obtained from three integrated accelerometers, was used to adjust the moment arm distance from the spine.

Early laboratory and field testing of the first prototype indicated that the system generally worked well with only minor problems associated with the visibility of the ultrasound transmitters which could be remedied with some rearrangement of the receivers on the backpack. It was clear that the weight of the backpack was excessive and would potentially influence the lifting style and, therefore, moment arm measurements, thus the need to refine the system's size and weight.

2.3. Phase 3: development of a load (force) monitoring system

An integral part of load moment determination involves the assessment of the load magnitude. Traditionally the lifted objects have been weighed using a simple spring scale. However, this weight measurement process can be very challenging when assessing load moment exposures in distribution center work. Unlike manufacturing operations where there may be little variation in the objects handled within a single job, often each item handled in distribution center work is unique and would therefore require that each item to be individually weighed. Weighing each item in these fast-paced environments would likely interfere with the worker's job performance, thus altering the work being measured. Additionally, weighing the object only provides the static load.

Recent biomechanical studies have indicated that static assessments grossly misrepresent the loading of the tissue (Granata and Marras, 1995, 1999; Marras and Granata, 1997; Marras, 1992). Hence, a load moment calculated using a static load may significantly under represent the risk imposed due to the dynamic load moment exposures. In sum, we needed to have automated instrumentation that could obtain both the static and dynamic loads to be used in the calculation of the static and dynamic load moments.

The recording of dynamic load characteristics during lifting requires the mass and acceleration characteristics of the load lifted be measured. In terms of instrumentation, this required that a series of strain gauges and accelerometers be placed in between the hands and the box lifted. LiftMates$^{\text{TM}}$ hand holds were used to house the instrumentation and serve as an interface between the load lifted and the hands (Fig. 3). The LiftMates handle is connected to a pin pad containing small (1/8") pins that grip the sides of cardboard boxes, thereby providing a handhold for the box. At the interface of the handles (hand attachment point) and the "pin pad" (load attachment point) are two digital load cells (strain gauges) and three analog accelerometers that record data at a rate of 1 KHz. The strain gauges and accelerometers are arranged in such a way that vertical and horizontal (towards or away from the body) load information are recorded. This arrangement makes it possible to record the mass and acceleration experienced by each hand during a lift thereby allowing the static mass and the dynamic load experienced by the hands to be obtained. Also shown in Fig. 3 are the ultrasound transmitters which were attached to the top and bottom of each handle.

2.3.1. Calibration testing

The output of the strain gauge handle force measurement system was compared in each direction (vertical and horizontal) over a series of known weights that varied from zero to 36 kg per handle. These calibrations indicated a linear relationship between true load and the load measured through the load cell ($r^2 = .99$) with the difference between tested weight and measured weight being less than a kilogram across the sampling range. An example of this calibration is shown in Fig. 4. Combinations of load directions were also tested.

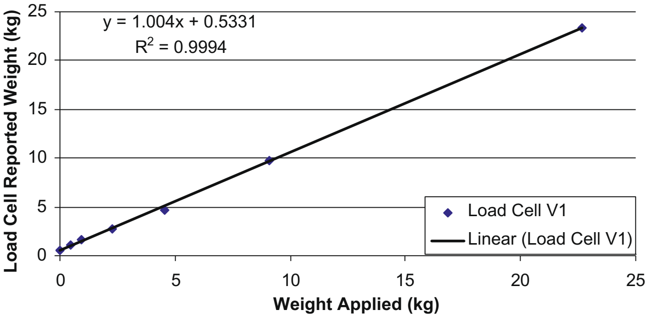

Fig. 4. An example of the handle load cell calibration showing the lower range of the calibration curve. This load range is most common in distribution centers.

2.4. Phase 4: development of a lighter moment tracking system

In this phase of the project, the goal was to integrate the load monitoring capabilities just described with a smaller, less cumbersome moment arm tracking system. Collectively these load and moment arm tracking technologies comprise the Moment Exposure Tracking System (METS). In order to accomplish this several changes were made compared to the original prototype. The resulting system (Fig. 5) weighed 5 kg (including the handles). In this system the ultrasound transmitters fire at a 12.5 Hz rate and are also coordinated by the main processor located on the backpack. The 4 sonic transmitters collectively transmit at a 50 Hz rate (50 Hz/4 = 12.5 Hz rate for each transmitter). The backpack accelerometer "chip" records data in the sagittal and lateral dimensions and is capable of monitoring forward and lateral orientation changes of the backpack. These data are simultaneously written to a flash card and broadcast via radio where it can be recorded using a wireless internet connection-enabled computer. The data collection software reads accelerometer data from each handle and the backpack, load cell data from each handle, and ranging (distance) data between each receiver and each transmitter. The software calculates the hand force and load mass using the load cell and accelerometer data. The accelerometer data are also used to determine the orientation (angles) of

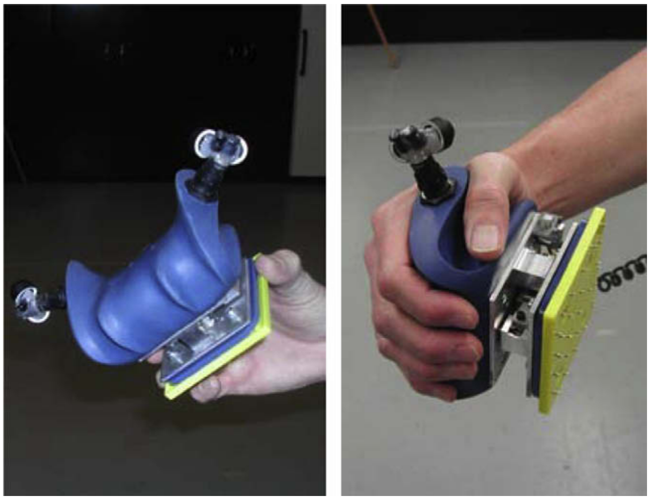

Fig. 3. The LiftMate$^{\text{TM}}$ handles instrumented with strain gauges and accelerometers for measuring static and dynamic loads and instrumented with ultrasound emitters for tracking hand position.

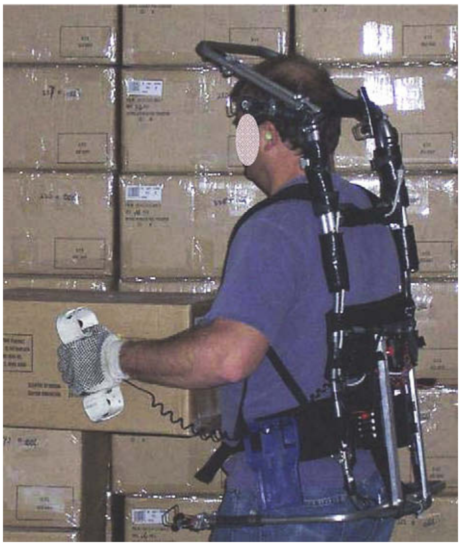

Fig. 5. The second generation Moment Exposure Tracking System (METS), weighing less than 5 kg, being used while a subject unloads a trailer in an apparel distribution center.

each handle in space as well as orientation of the backpack in space.

In triangulating the location of the target, the software performs a least squares fit on the ranging data to determine the location of each handle relative to the backpack using the known locations of each receiver on the backpack. Where the ranging data disagrees on the location of each transmitter or if data are absent for a particular transmitter, the software uses the orientation data from the handle load cells and performs multiple iterations to determine the optimal transmitter location. This optimization initially places the transmitter at a set point in front of the body and calculates the residuals between the ranging data and the initial placement. The transmitter is then moved a small amount in one direction and residuals recalculated. If these residuals are smaller than the original, the transmitter is iterated farther in that direction. If not, another direction is attempted. This iteration continues until the residuals do not decrease if the transmitter is moved in any direction. Constraints are used to keep the software from finding a duplicate solution that would place the transmitter behind or inside the body. After the optimization, the location of each transmitter is then used to locate the box (midway between the hands).

Anthropometric data (height, weight, depth and breadth at the xyphoid process and the iliac crests) are used to identify the location of lifter's L5/S1 joint. The software then calculates the horizontal distance between the box and L5/S1 as well as the height of the box from the floor. These data are then combined with the force data to determine moment.

Operationally, the software performed several functions. First, the software was used to "initialize" the system by allowing the user to calibrate the system relative to any unique conditions and assess the status of the signal at each ultrasound receiver. Second, the software could be used to assess system status and check the "visibility" of each receiver, and monitor the trunk angle and the load location relative to L5/S1 at any point in time. Third, the software recorded continuous information used to calculate the instantaneous load moment during each lifting event. Other recorded aspects of a lift event included: time of day, time since last lift, duration of lift, initial moment arm, continuous moment arm, final moment arm, load acceleration, box weight, dynamic force, peak static moment, cumulative static moment, peak dynamic moment, cumulative dynamic moment, average dynamic moment, vertical location of box. And fourth, the software kept track of cumulative data over a work period by accumulating specified events including non-load (rest) periods.

2.5. Phase 5: receiver "vision" optimization

Placements of the sonic receivers on the backpack frame are critical for optimal triangulation of the handles. Two techniques were used to determine the optimal locations of the eight receivers on both the prototype moment arm tracking system and the second generation METS. First, given the cone of vision of the receivers (90°) the field of view was estimated graphically by working backwards from the desired sample space so that the sample space could be "seen" by at least three receivers. Second, a process of systematic testing and comparison with a laboratory based magnetic tracking system (validation testing - next section) was employed where receiver configurations were iteratively altered based upon system performance on more and more rigorous realistic test conditions. While twenty nine different configurations were studied with the second generation METS, configurations that included receivers placed at the backpack belts proved unacceptable errors. Thus, all receivers were fixed to the backpack frame. However, accuracy of the METS peaked when the 8 receivers were not in the same plane.

2.6. Phase 6: system validation and testing

The system and sensor configurations were evaluated using a magnetic motion capture system (The Motion Monitor^{TM}) for accuracy. A systematic process was used to test: 1) the prediction of a static target's location with an upright backpack system, 2) the prediction of static target's asymmetric location relative to the backpack, 3) the accuracy of the backpack's measured forward and lateral flexion angles, 4) the accuracy of the moment arm distances with varying backpack flexion angles, 5) the ability of the system to track asymmetric movement of a target, 6) the accuracy of the backpack system under full dynamic motion of the backpack target, 7) the accuracy of the predicted vertical load location, and 8) the comparison between the METS and the Lumbar Motion Monitor sagittal and lateral flexion angles.

2.6.1. Test 1: The prediction of a static target's location with an upright backpack system

The purpose of this test was to evaluate the accuracy of the system's predicted moment arm distance relative to physical hand location measurements and hand locations derived from the magnetic tracking system.

2.6.1.1. Methods. Hand location measurements employed a series of plum bobs to accurately assess moment arm distance. Combinations of three different target heights, three different moment arm lengths, and three different asymmetries were tested both with and without a person attached to the METS over a total of 54 different test conditions. Eleven different combinations of configurations and software were used to test this system.

2.6.1.2. Results. Over the various configurations AAE varied from 2.3 cm to 7.6 cm. The final configuration (shown in Fig. 6) yielded an AAE of 2.3 cm with computationally intensive software. The AAE changed to 4.1 cm when more computationally efficient software was used to analyze the data. No differences in system visibility or performance were observed with or without a human

Fig. 6. The testing of static target locations relative to an upright fixed backpack location.

wearing the METS under these conditions. For the final configuration AAE was generally invariant to target height and moment arm distance.

2.6.2. Test 2: The prediction of static target's asymmetric location relative to the backpack

One particular concern was if a person lifts asymmetrically while wearing the backpack, the visual field of the METS may not be adequate to resolve the hand locations. Thus, the objective of this test was to test the adequacy of the receiver vision when lifts that have asymmetric origins and asymmetric destinations were performed.

2.6.2.1. Methods. Three subjects performed a series of lifts while a video camera recorded the asymmetry in their lifts from a vantage point directly overhead. Each subject was asked to lift boxes from 6 different asymmetric locations (15, 30, and 45° asymmetry clockwise and counterclockwise) from two different heights (low and high) off the floor. Dependent variables consisted of the maximum asymmetry angle between the box and the sagittal origin of the backpack.

2.6.2.2. Results. The average lift asymmetry across subjects was 16° with a standard deviation of 9°. More importantly, it was found that the asymmetric lifts were well within the sonic receiver's field of view and therefore could be monitored easily by the METS.

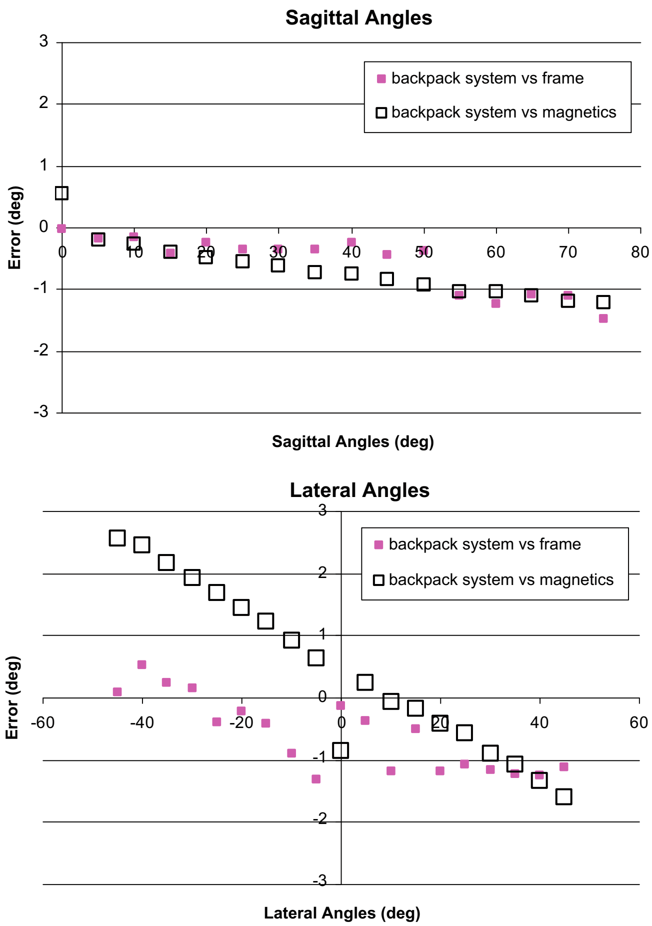

Fig. 7. The differences (error) in sagittal and lateral flexion angles between the backpack system and the physical measurement frame and between the backpack system and the magnetic motion capture system.

2.6.3. Test 3: The accuracy of the backpack's measured forward and lateral flexion angles

The ultrasonic system tracks the position of a target relative to the backpack upon which the receivers are mounted. However, horizontal moment arm distance is defined as the horizontal distance from the load lifted to the spine. Thus, if a person is lifting while the torso if flexed, the sonic system can locate the target relative to the backpack but the position of the backpack relative to the world must be tracked in order to determine the target location relative to the spine. Hence, accurate assessments of sagittal and lateral backpack angles are crucial to the successful determination of moment arm distance during a lift. The purpose of this test was to validate the angles obtained from the backpack accelerometer system.

2.6.3.1. Methods. The backpack's accelerometer system was mounted upon a reference frame that could be adjusted to sagittal plane inclination angles ranging from 0 to 75° forward flexion and +/−45° of lateral flexion. In addition to the physical measurement from the reference frame, the Motion Monitor system was also used to measure the inclination angle of the METS accelerometer system.

2.6.3.2. Results. The results of this assessment are shown in Fig. 7 for sagittal and lateral bending. The figure displays the error in predicting sagittal and lateral bending angles using the backpack system as compared with both the magnetic system and a rigid calibration frame. Regression equations were created to correct for these errors and are now used by the system software to predict angle. Using the software correction, the AAE for both sagittal and lateral bends was reduced to 0.6°.

2.6.4. Test 4: The accuracy of the moment arm distances with varying backpack flexion angles

Once the backpack angles prediction were validated, the moment arm distance predictions needed to be verified through a test in which the backpack was oriented in a series of flexed postures (as would be expected during lifting).

2.6.4.1. Methods. Two tests were performed. In each test, the backpack was tested in 10° increments over a 90° range of flexion. In the first test the box was at two fixed vertical locations while maintaining a fixed horizontal distance from the backpack. In the second test, the box was rotated with the backpack, thereby maintaining a constant spatial relationship to the backpack during the flexion test. Dependent measures consisted of the AAE between the moment arm distances predicted by the METS and those predicted by the magnetic motion capture system described earlier. Eighteen different configurations were tested in these analyses.

2.6.4.2. Results. The AAE varied over the configurations from 2.5 to 13.2 cm. The final (optimal) configuration yielded an AAE of 3.6 cm with a standard deviation of 1.3 cm. Under fixed target conditions the AAE was below 2.5 cm.

2.6.5. Test 5: The ability of the system to track asymmetric movement of a target

The next step in the iterative process called for an assessment of the effects of dynamic motion of the target relative to the backpack under changes in target asymmetry and changes in target height.

2.6.5.1. Methods. Three subjects wore the METS and moved boxes asymmetrically from side to side. The backpack was generally in an upright position during this evaluation but the box origins and destinations varied in vertical height between waist and shoulder height. Both the sonic METS and the magnetic motion capture

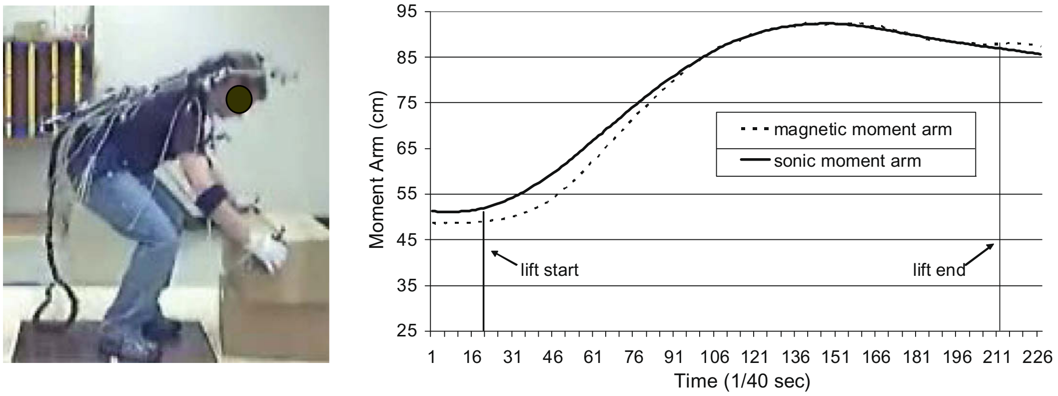

Fig. 8. Testing the moment arm calibration measurements obtained during dynamic lifting from knee level. The graph shows the time varying moment arm as a box was lowered from the waist level carry position to a position 46 cm above the floor (photo).

system were used to simultaneously estimate the continuous moment arm distance of the box from the spine over the course of the lift. Dependent measures consisted of AAE as well as the R^2 value describing the amount of dynamic variability accounted for by the two measurement systems. Six different system configurations performed well enough on previous tests were evaluated under these conditions.

2.6.5.2. Results. The AAE varied among the configurations from 2.5 cm to 11.7 cm. R^2 values varied from 0.47 to 0.93. The final configuration yielded an AAE of 4.8 cm and an R^2 value of 0.93.

2.6.6. Test 6: The accuracy of the backpack system under full dynamic motion of the backpack and target

The purpose of this test was to evaluate the potential error in the METS under fully dynamic lifting activities relative to the data captured by the magnetic motion capture system.

2.6.6.1. Methods. In this assessment three subjects were asked to lift and lower boxes at a normal speed from and to four different heights (46, 69, 91, and 114 cm) from and to a carrying (waist level) position. The sonic METS estimates of moment arm distances were compared with magnetic motion capture system's predictions of moment arms (Fig. 8). Both AAE and R^2 were used as measures of performance. Only the top three configurations from our previous tests were considered for this testing.

2.6.6.2. Results. All three configurations performed well with excellent tracking of the target. Fig. 8 shows an example from the final configuration during a knee level lift. Note the correspondence between the METS moment arm and the moment arm obtained with the magnetic tracking system. Overall, peak AAE varied among the configurations from 3.8 to 4.1 cm. R^2 values varied from average of 0.77 to 0.99. The final configuration yielded an AAE of 3.8 cm and an average R^2 of 0.98.

2.6.7. Test 7: The accuracy of the predicted vertical load location

The purpose of this test was to determine if the METS could accurately quantify this parameter, one that was not in the original specification of the METS design.

2.6.7.1. Method. An evaluation was performed to assess the ability of the system to monitor load height during transfers from seven known origins to seven known destinations (including asymmetric motion) during a series of lifting tasks. AAE and R^2 measures served as the dependent variables for this assessment. Two system configurations were evaluated.

2.6.7.2. Results. The final configuration of the METS resulted in an AAE of 2.2 cm between the predicted and observed vertical heights and the time varying data had an R^2 value of 0.89.

2.6.8. Test 8: A comparison between the METS and the Lumbar Motion Monitor sagittal and lateral flexion angles

A final test compared the relationship of sagittal flexion-extension and lateral flexion angles between the METS and another validated device designed for measuring torso motion in the workplace, the Lumbar Motion Monitor (LMM).

2.6.8.1. Methods. Ten subjects wore both the METS and the LMM systems at the same time. The backpack frame used in the METS was slightly modified to avoid interference with the LMM. In addition to the LMM and METS, an electro-goniometer was also used to monitor the rotation of the pelvis in the sagittal plane. Data from both systems were sampled at 100 Hz and synchronized via a time marker.

The subjects started the sagittal angle comparison test from a neutral upright posture. They were then instructed to maximally hyper-extend, then flex forward to a full flexed posture, and then return to the neutral upright posture in a single continuous motion. During the lateral angle comparison, the subjects were asked to laterally flex to the left from an upright neutral posture as far as they could, then laterally flex as far as possible to the right side, and then back to an upright neutral posture.

2.6.8.2. Results. The linear regression (Eq. (1)) indicated there was good correspondence between the LMM and METS with respect to sagittal angle (R^2 = 0.90).

$$\text{METS sagittal angle} = -0.03195 + 1.53414^{*}\text{LMM sagittal angle} \tag{1}$$

Adding the pelvic rotation into the model (Eq. (2)) improves upon the relationship (R^2 = 0.95).

$$\begin{aligned}\text{METS sagittal angle} = {} & -0.41514 + 0.82330^{*}\text{LMM sagittal angle} \\ & + 0.75160^{*}\text{pelvic tilt}\end{aligned} \tag{2}$$

The regression model for the lateral flexion angle also showed a strong linear relationship between the two motion capture systems (R^2 = 0.85) and is shown in Eq. (3).

$$\text{METS lateral angle} = -0.52708 + 1.93044^{*}\text{LMM lateral angle}. \tag{3}$$

In summary, these results indicate that data obtained using the LMM can be used to predict METS measures, and vice versa, thereby facilitating the interpretation of laboratory and field studies utilizing these pieces of equipment.

3. Discussion

The initial aim of this research was to develop instrumentation so that the horizontal distance between the hands and the spine can be accurately measured for each lift performed over the course of an entire work shift. The biomechanical significance of the load moment has been established both in biomechanical and epidemiological studies (Schipplein et al., 1995; Marras et al., 1999). The resulting Moment Exposure Tracking System (METS) could not only measure the horizontal distance between the hands and the spine (moment arm), but also the load weight, dynamic hand forces, trunk kinematics, box kinematics, and duration of exertions and rest periods. The phases of the development and their corresponding tests ensure adequate accuracy of the system was obtained. It must be kept in mind that traditional hand measurement error of moment arm averaged 10.9 cm. The goal was to reduce of measurement error to less than 6 cm. A series of tests showed that the accuracy of METS reached 3.8 cm with an R^2 of 0.98, thereby significantly improving upon the accuracy of the traditional tape measure method. The accuracy of the load measurement was also within half a kilogram. Without the need to manually measure moment arms, weights, start and ending heights, this data collection system is well suited for studies of dynamic distribution center jobs where weights and lifting conditions change with each lift performed. Moreover, because the instrumentation continually tracks these data without interfering with a worker's routine, we should be able to obtain reliable data describing the cumulative exposures and duty cycles in these distribution operations.

One of the important features of the METS is its capability to measure the dynamic loads imposed on the biomechanical system. In the past the load of each box handled by the workers can only be weighed to get the static load. Several studies have shown that static assessments under-represent the loading of the tissue (Granata and Marras, 1995, 1999; Marras and Granata, 1997; Marras, 1992). METS is capable of measuring dynamic hand forces in both the lifting/lowering and push/pull directions, thereby allowing the dynamic load moment to be calculated for each lift. This provides us the opportunity to assess the true load moment exposures in jobs where people are often working quickly as they are continually being assessed via productivity monitoring systems.

In order to develop the instrumented moment monitor system several technologies were considered. These included microwave transmission, magnetic tracking, goniometric/gyroscopic systems. In our initial evaluation of these approaches, all were found to have limitations. The microwaves, which work on the principle of reflecting signals off of a target and use timing data to measure the distance, worked reasonably well for targets that were perpendicular to the microwave transmission source but not for non orthogonal targets. Magnetic tracking technology had the limitation of system weight and potential interference with metallic structures such as the racking systems. The goniometric approach involved tracking the hands relative to the back using essentially a "suit of sensors". While this system would allow multi degree of freedom measurements at the major articulations of the body, the shoulders presented a significant challenge and such a system would need to be calibrated for each individual worker, thereby requiring a substantial amount of set up time. None of these systems had any provision for measuring hand loads. The force data would still need to be integrated with these kinematic data at some later point.

One of the limitations of this system is that the person must lift while wearing a rigid backpack frame. This does change the spine kinematics in that the twisting motions are notably restricted. Another limitation is that the lifted objects need to be handled using the instrumented pin-gripping handles. This does change the human object interface, and may alter the lifting mechanics. For example, the handles may reduce the forward spine flexion as the effective hand height is higher now that individuals do not need to get their fingers under the bottom of the box. Such changes would be expected to reduce the spine loads (Lavender et al., 2003). Additionally, the handles may reduce the speed of lifting, which in turn reduces the dynamic loading of the spine (Lavender et al, 1999; Marras and Granata, 1997). Taken together, these limitations suggest that assessments using the backpack and handles may provide conservative estimates of load moment exposures. However, we believe these subtle changes in lifting technique observed when working with this device will have a relatively minor influence upon the parameters describing load moment exposures in distribution center jobs.

In conclusion, the Moment Exposure Tracking System developed through this process provides validated estimates of dynamic load, load moment, spine posture, and exposure history that can be used for sampling lifting tasks that continually vary in terms of spatial configurations and load magnitudes. As such, this instrumentation provides a means for accurately describing the magnitude and the variation in lifting exposures encountered in distribution center jobs.

Conflict of interest statement

None declared.

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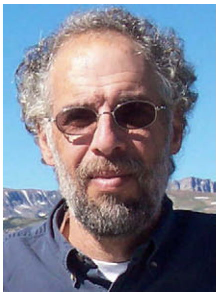

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