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Instrumentation

Accuracy of a three-dimensional lumbar motion monitor for recording dynamic trunk motion characteristics

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Abstract

There has been an abundance of evidence in the past decade that indicates that the asymmetric positioning as well as the dynamic action of the trunk during work greatly affects the ability of a worker to perform a lifting task. This is true because trunk strength decreases as the trunk moves more asymmetrically and more rapidly. Loading of the spine is also believed to increase under these conditions, since significantly greater trunk muscle activity has been observed under these conditions. Therefore, we must begin to document the asymmetric positions as well as the dynamic motion characteristics of the trunk when workers are exposed to various work tasks. This paper describes a lumbar motion monitor (LMM) that has been developed for this purpose. The LMM is an exoskeleton of the spine that is instrumented so that instantaneous changes in trunk position, velocity and acceleration can be obtained in three-dimensional space. The current study has assessed the accuracy and reliability of the LMM to measure such motion components. The results of this analysis indicate that the LMM is extremely reliable and very accurate. This study has shown that the LMM is about twice as accurate as a video-based motion evaluation system. The benefits and implications of using an LMM for work assessment and clinical use are discussed.

Relevance to industry

This paper describes a means to monitor trunk motion characteristics in the workplace or in the clinic. Documentation of such motions will facilitate the understanding of how certain workplace designs contribute to occupational low back disorder risk. In addition, the device could be used as a clinical assessment tool. This device provides a means for one to compare on the job trunk motions with laboratory studies.

Keywords

Back, strength, kinematics, trunk strength, asymmetry, low back disorder.

Introduction

Traditionally, the biomechanical assessment of low back disorder (LBD) risk in the workplace has been accomplished with static, two-dimensional evaluations of trunk loading. Common assessment techniques such as the one outlined by the Work Practices Guide for Manual Lifting (NIOSH, 1981) predict the compression on the lumbro-sacral (L5/S1) joint of a worker during a sagittally symmetric lift. These spine compression estimates are compared with spine compression tolerance data to determine whether the lift is safe. This guide assumes the lift is slow and smooth and does not contain any appreciable acceleration. The assumption of a slow smooth lift is necessary because the trunk loading is based upon isometric biomechanical analyses that assume the worker is in a static, frozen position.

There has been an abundance of evidence over this past decade that indicates we must begin to explore the three-dimensional dynamic motion components of a work environment. Epidemiological studies (Andersson, 1981; Pope, 1989) have shown that the risk of suffering an LBD increases significantly due to asymmetric demands (such as twisting) on the trunk during lifting. Bigos et al. (1986) examined the factors associated with LBD in a company of over 31,000 employees where manual materials handling was prevalent. This study concluded that the risk of LBD was three times greater for workers performing dynamic lifts compared to workers who were exposed to awkward static postures.

The biomechanical costs of three-dimensional dynamic lifts have also been explored recently. Marras, King and Joynt (1984), and Marras (1986; 1987), have shown that trunk strength is reduced dramatically and muscle activity increases dramatically with increasing velocity of motion. Marras and Mirka (1989; 1990) have also shown that trunk asymmetry and acceleration have similar effects upon the trunk. Finally, Marras and Sommerich (1991a,b) have shown that under dynamic

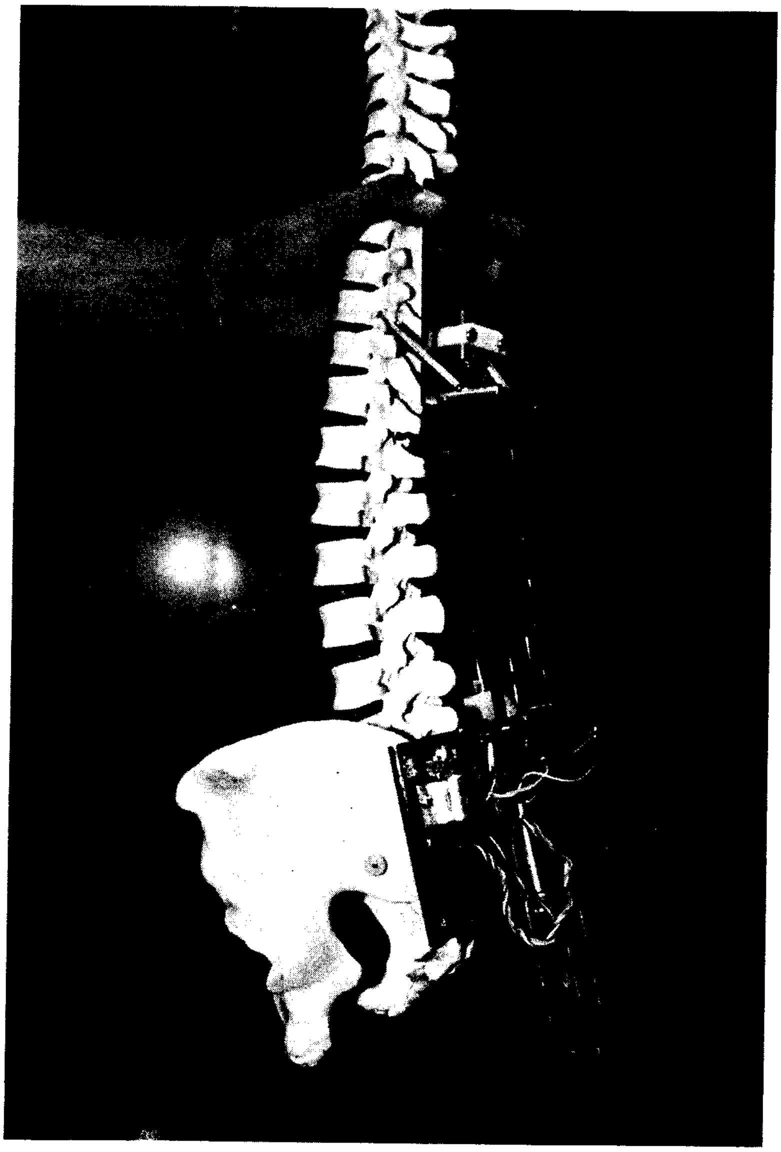

Fig. 1. The LMM exoskeleton compared to an anatomical model of the spine.

conditions the predicted compressive and shear forces on the spine increase significantly.

This information indicates that we should begin to examine the dynamic, three-dimensional motions of the trunk in the workplace. The major problem in measuring the dynamic, three-dimensional components of the trunk is that it is difficult to monitor and record such actions in the workplace. Video-based computer motion analysis systems are used for this purpose but they are expensive and often technically unable to accurately monitor a worker under typical work conditions. These systems require that joint markers be placed upon the worker that must be viewed by the video cameras at all times. In many industrial environments these markers may not be visible by the video cameras due to machinery, equipment, assembly lines, other workers, mist, poor lighting, etc. The analysis is also limited by the field of vision of the camera. Jobs that require the worker

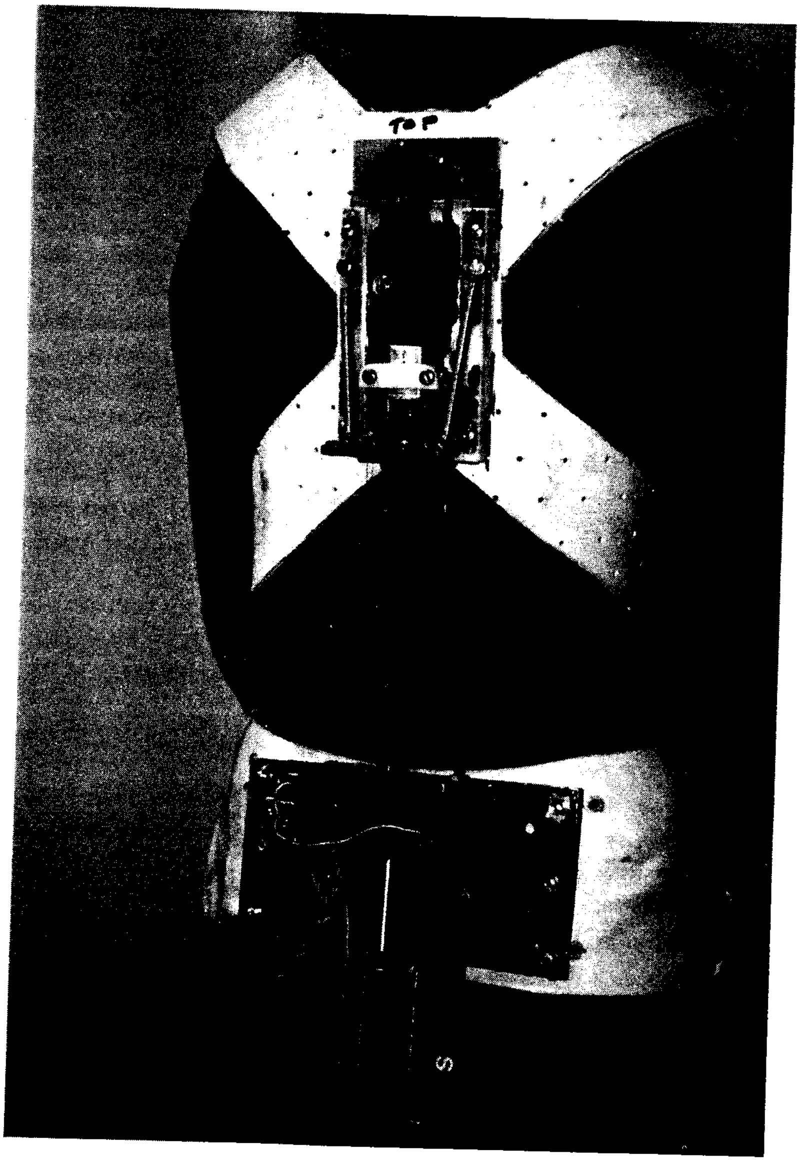

Fig. 2. The LMM worn by a subject.

to move to several work stations are extremely difficult to observe. Therefore, there is still a need to measure and document the three-dimensional motions of the trunk in the workplace.

Lumbar motion monitor

A system has been developed, called the lumbar motion monitor (LMM), to document the three-dimensional components of trunk motion in the work environment that can overcome these obstacles. This system is modeled after the trunk motion control system of the back. The spine is guided by the spinous processes and transverse processes that form a T section in the posterior aspects of each spinal vertebra. These sections are connected to each other with ligaments and muscles that envelop the facet joints of the spinal segments. The LMM is an exoskeleton of the spine that replicates the motion of these T sections in the lumbar spine. Figure 1 shows the LMM exoskeleton compared to an anatomical model of the spine. This exoskeleton is worn on the back of the worker and moves along with the worker. The ends of each edge of the exoskeleton T section is connected via wires to three potentiometers in the base of the LMM. These wires differentially change the voltage readings in the potentiometers as the exoskeleton moves forwards, backwards, or to the sides. A cable is also placed through the junction in each T section and is connected to a fourth potentiometer. This potentiometer changes as the exoskeleton is twisted. The details of the LMM design can be found in Marras, Davis, Miller and Mirka (1990).

The LMM is attached to the thorax and the pelvis with a semi-rigid plastic material (Orthoplast) that is pre-molded to the worker. This provides two stable 'anchors' to the middle spine and the pelvis. The LMM is shown on a subject in figure 2. Thus, the LMM measures the difference in spine position of the lumbar spine (as a unit) relative to the pelvis.

The potentiometer signals are interfaced with an analog-to-digital (A/D) converter and the signals are recorded on a microcomputer. The signals have been calibrated to correlate with trunk angle. The signals are then processed to determine position, velocity, and acceleration of the trunk as a function of time.

The objective of this paper is to assess the accuracy and repeatability of the LMM in its ability to document position, velocity and acceleration characteristics in three-dimensional space.

Method

Approach

The goal of this paper is to evaluate the accuracy and repeatability of the LMM in its ability to predict position, velocity and acceleration. In order to accomplish this goal the LMM position was compared with known positions of the LMM in space. This was accomplished via a reference frame that permitted motion in three-dimensions. In order to evaluate the ability of the LMM to measure velocity and acceleration, the LMM was compared with a comercially available video-based motion evaluation system (Motion Analysis). Both the LMM and the Motion Analysis systems compute velocity and acceleration by differentiating the position signal gathered by the system. Thus, the velocity and acceleration accuracy are dependent upon the ability of the systems to accurately measure position. Therefore, the position accuracy of the Motion Analysis system was also measured in the reference frame. Hence, in this investigation, LMM position was gauged against the reference frame position, whereas velocity and acceleration were gauged relatively (to position accuracy) against the Motion Analysis system.

Apparatus

The LMM is a device capable of assessing the instantaneous position of the lumbar spine in three-dimensional space. The LMM is essentially an exoskeleton of the spine that has been described previously. Voltage outputs were transmitted to an A/D board and then to a portable 386 micro computer. Voltage readings of the potentiometers are converted into angular position using a regression (calibration) model. The angular velocity and acceleration are obtained through numerical differentiation. Smoothing is also performed prior to successive differentiation. The computer also evaluates various motion compo-

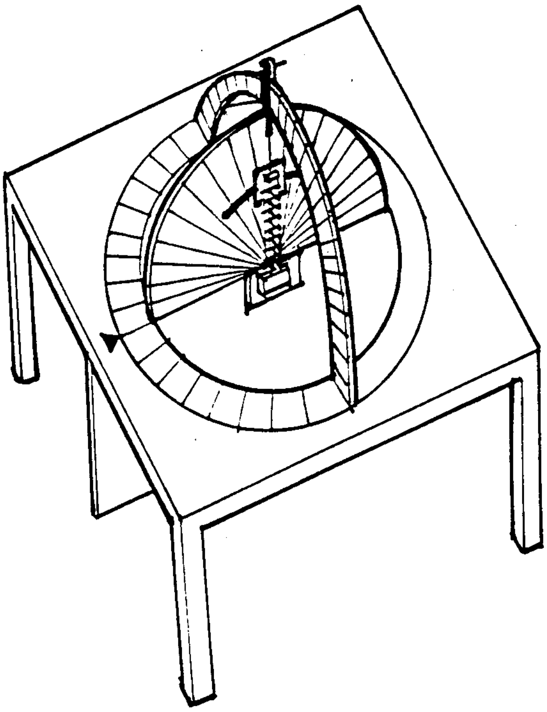

Fig. 3. The three-dimensional reference frame.

nent profiles in each plane of the body (frontal, sagittal, and transverse).

A three-dimensional reference frame has been developed to calibrate the LMM with respect to the device's position in three-dimensional space. The frame consists mainly of three sections that correspond to the three body planes (frontal, sagittal, and transverse planes). The LMM can be placed in this reference frame and its position can be specified in any combination of the three planes. Each section has a series of marks indicating the position of the LMM, in five-degree increments, with respect to the center of the frame. See figure 3 for a depiction of the frame.

A two-dimensional Motion Analysis (MA) system by ExpertVision was used to determine how the LMM compares to this system of motion quantification in a certain two-dimensional (2-D) space. The MA consists mainly of a video camera, a VCR, a video signal processor and a computer. The video camera captures the motion of a specific number of light emitting diodes (LEDs) placed on the object in motion in the 2-D space of interest. In this experiment, several LEDs were placed upon the upper chest plate and lower base plate of the LMM. The video signal is transmitted to the video signal processor, via the VCR. The video signal processor tracks the motion of the moving LED at a selected rate. The processed signal is transmitted to a computer for analysis. The computer software determines the path of a selected moving LED. Linear distance traveled by the moving LED, in cm, or angular motion, in degrees, with respect to a fixed LED (bearing) can be determined depending on the type of motion undertaken (linear or angular). Through numerical differentiation, the velocity and acceleration (angular velocity and acceleration) of the moving LED are determined.

Procedure

The LMM was placed on its calibration frame in order to determine the actual range of motion (in degrees) of a given trial in a given plane. Two LEDs were placed on the LMM; one on its top (moving) part and another on its bottom (fixed) part. This procedure ensured that the moving LED would follow the exact path that the LMM would undertake. The video camera was aligned perpendicular to the 2-D space in which the LEDs (LMM) moved.

For each plane (frontal, sagittal and transverse), the experimenter moved the LMM in a pre-selected range of angular motion (ROM). These ROMs consisted of either 15, 30 or 45 degrees of range. The actual ROM that the LMM (and the MA LEDs) passed through was controlled by restricting the motion of the LMM to any selected ROM on the frame using a clamp to define the end point of the motion. The values of the ROM obtained by both the LMM and MA systems were compared to the actual ROM (pre-selected ROM on the calibration frame). For each ROM in both the frontal and sagittal planes, the transverse plane of the frame was set at one of the following asymmetry levels (degrees of deviation from the zero degrees mark): 15 degrees, 30 degrees, and 0 degrees (no deviation). Three trials were taken for each ROM (5 trials for ROMs in the transverse plane) in order to obtain an estimate of the angular position. All trials were performed, by the experimenter, at relatively comparable velocities and accelerations. The exact breakdown of every condition

Table 1

Average deviations, in degrees, between actual range of motion (ROM) in the frontal plane and average range of motion given by the LMM and the MA systems, respectively. Three levels of asymmetry (angular positions in the transverse plane) were preset before collecting a trial: 0, 15, and 30 degrees.

Rom (deg.)	Asymmetry (deg.)	LMM	MA	Dev. (LMM) (deg.)	Dev. (MA) (deg.)
15	0	14.71	16.55	0.29	1.55
15	15	15.59	16.85	0.59	1.85
15	30	16.42	16.79	1.42	1.79
30	0	28.91	32.87	1.09	2.87
30	15	29.75	32.42	0.25	2.42
30	30	33.36	33.61	3.36	3.61
45	0	41.24	48.72	3.76	3.72
45	15	43.11	48.61	1.89	3.61
45	30	47.75	49.50	2.75	4.50
			Average:	1.71	2.88

(plane/ROM/asymmetry) will be presented later in the results section.

Data were collected for each trial at 60 Hz for a period of three seconds. Since the video-based MA system also samples at 60 Hz, this ensured that the LMM and MA accuracies would be a function of the devices and not the sampling rate. For each trial, three pieces of information were taken from each system for analysis purposes: the range of motion (ROM), in degrees; peak angular velocity (in deg/sec), and peak angular acceleration (in deg/sec/sec).

A second set of data were collected for the expressed purpose of testing the repeatability of the LMM. In this study, 10 repetitions of LMM motions were performed in each of 20 different ranges of motion performed in the frontal, sagittal and transverse planes. These positions were controlled with the reference frame in a manner similar to the one described earlier.

Analysis

The measure of performance for the position variable in this study was LMM predicted deviation from the actual position as defined by the reference frame. Average deviation over all conditions serves as a concise indicator of accuracy. The measure of performance for the velocity and acceleration variables were the agreement be-

Table 2

Average deviations, in degrees, between actual range of motion (ROM) in the sagittal plane and average range of motion given by the LMM and the MA systems, respectively. Three levels of asymmetry (angular positions in the transverse plane) were preset before collecting a trial: 0, 15, and 30 degrees.

Rom (deg.)	Asymmetry (deg.)	LMM	MA	Dev. (LMM) (deg.)	Dev. (MA) (deg.)
15	0	14.50	15.98	0.50	0.98
15	15	15.03	17.00	0.03	2.00
15	30	15.71	16.78	0.71	1.78
30	0	29.56	30.86	0.44	0.86
30	15	28.78	30.91	1.22	0.91
30	30	31.06	30.14	1.06	0.14
45	15	44.34	40.32	0.66	4.68
45	30	48.07	41.37	3.07	3.63
			Average:	0.96	1.87

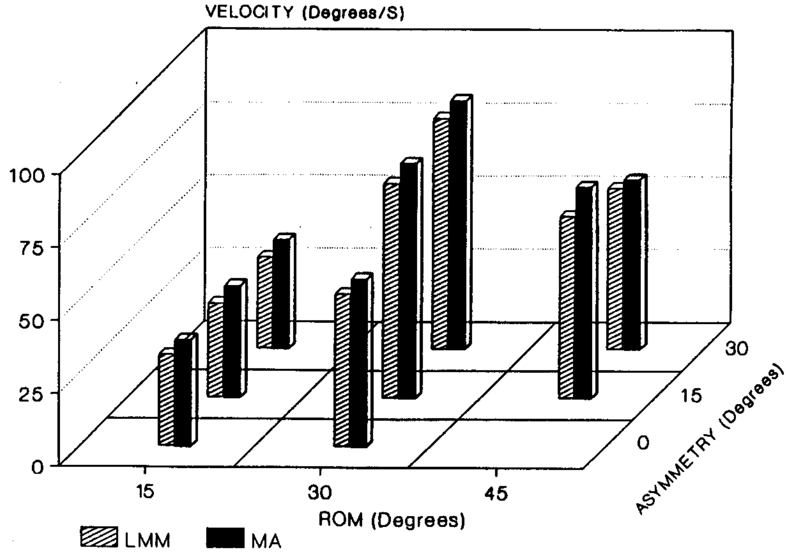

Fig. 4. The peak velocity characteristics of the LMM and MA as a function of ROM in the sagittal plane and asymmetry in the transverse plane.

tween the peak angular velocity and peak angular acceleration predicted by the LMM and MA systems. The correlation coefficient was used as an indicator of this measure.

Results

Tables 1, 2 and 3 present the average deviations, in degrees, between the actual ROM and

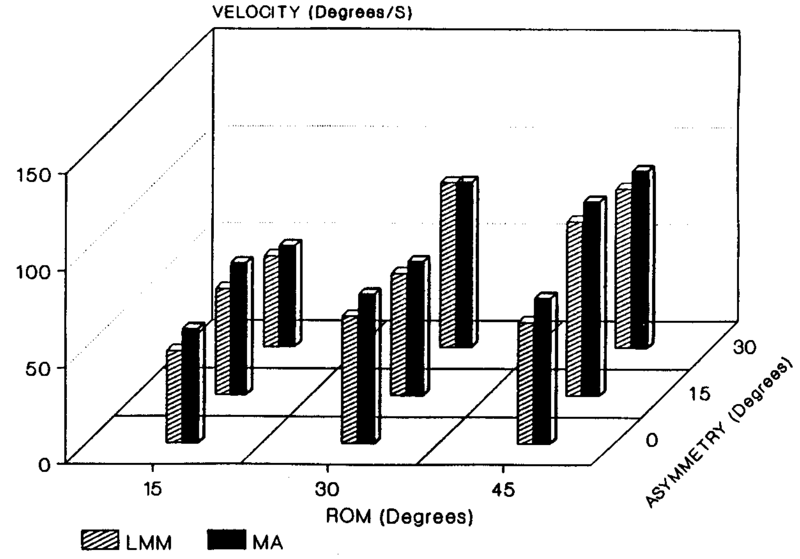

Fig. 5. The peak velocity characteristics of the LMM and MA as a function of ROM in the frontal plane and asymmetry in the transverse plane.

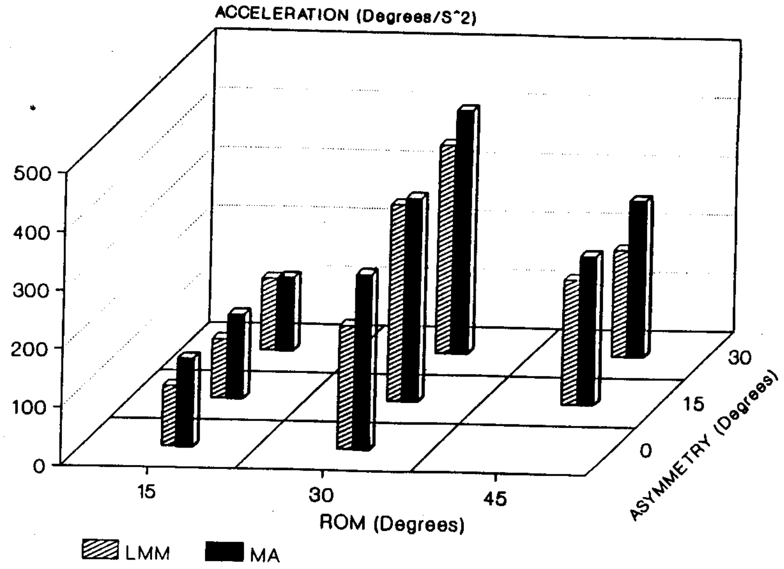

Fig. 6. The peak acceleration characteristics of the LMM and MA as a function of ROM in the sagittal plane and asymmetry in the transverse plane.

ROMs predicted by the LMM and MA for the frontal, sagittal and transverse planes, respectively. Note again that for the frontal and sagittal planes, each ROM was tested three times and collected in combination with a certain asymmetry level (0, 15, or 30 degrees). In general, average deviations for the LMM in the frontal, sagittal and transverse planes were 1.71, 0.96, and 0.50 degrees respectively. Also, it should be noted that the deviation between the LMM and the reference frame ROM is related to the asymmetry angle under consideration (see tables 1 and 2). It

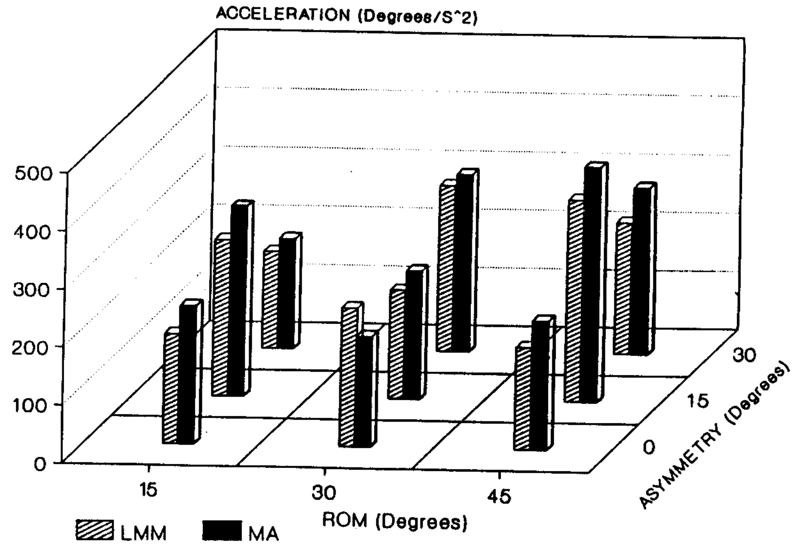

Fig. 7. The peak acceleration characteristics of the LMM and MA as a function of ROM in the frontal plane and asymmetry in the transverse plane.

Table 3

Average deviations, in degrees, between actual range of motion (ROM) in the transverse plane and average range of motion given by the LMM and the MA systems, respectively.

ROM (deg.)	LMM	MA	Dev. (LMM) (deg.)	Dev. (MA) (deg.)
14	13.42	13.72	0.58	0.28
28	27.57	28.28	0.43	0.28
		Average:	0.50	0.28

is also evident that the average deviations of the MA system were generally about twice those of the LMM.

In the present setup, there was no reference system available to determine the actual velocity and acceleration undertaken by the LMM. However, the LMM was compared to the MA in relative terms. This was necessary since the positions estimated by the MA deviated by a much greater degree than did the LMM estimates. Thus, the 'standard' measure of velocity and acceleration (MA) would be imprecise since the velocity and acceleration were determined via the position differentiation. Figures 4 and 5 depict the peak velocity of the LMM and MA for every ROM/Asymmetry combination in the sagittal and frontal planes, respectively. Figures 6 and 7 de-

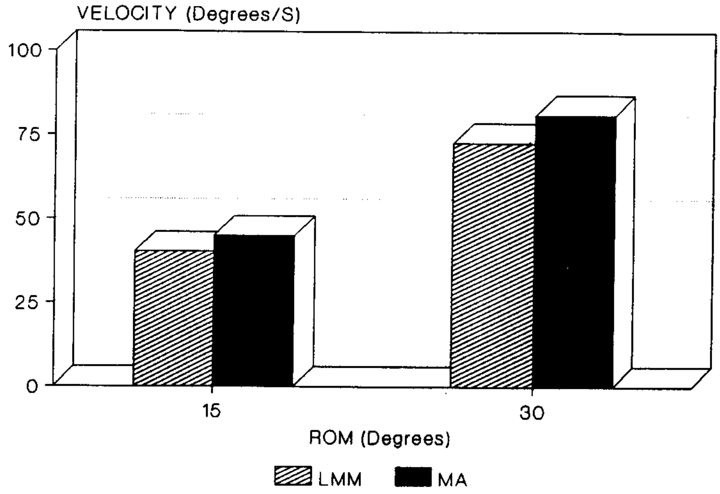

Fig. 8. Peak velocity characteristics in the transverse plane as a function of 15- and 30-degree ROMs.

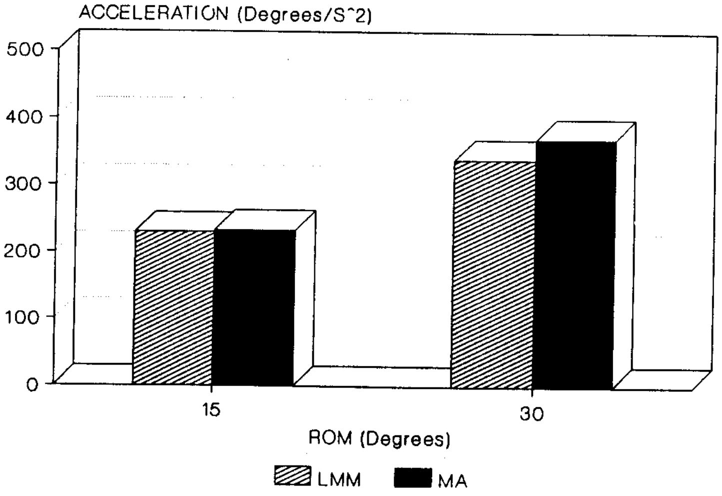

Fig. 9. Peak acceleration characteristics in the transverse plane as a function of 15- and 30-degree ROMs.

Table 4

Correlations of angular velocity (velocity) and angular acceleration (acceleration) of the MA system in the frontal, sagittal, and transverse planes with velocity and acceleration of the LMM system.

Plane	Correlation [a]	
	Velocity	Acceleration
Frontal	0.95	0.95
Sagittal	0.99	0.96
Transverse	0.99	0.99

[a] $p < 0.0001$

pict the peak acceleration in the sagittal and frontal planes, respectively. From figures 4 through 7, it is apparent that the LMM consistently yielded slightly lower values of velocities and accelerations with the exception of acceleration in the frontal plane at 30/0 degrees ROM/Asymmetry. However, the LMM velocity and acceleration estimates generally follow those of the MA system. No other obvious trends in acceleration/velocity of the two systems were observed due to different levels of asymmetry, ROM or combination of the two.

Figure 8 shows the peak velocity of LMM and MA for the 15 and 30 degrees ROM in the transverse plane. Figure 9 shows the corresponding accelerations in the transverse plane.

Again the velocities and accelerations revealed by the LMM were slightly lower than their corresponding MA values. This was not unexpected given that the MA system overpredicted position. However, LMM and MA velocity and acceleration could still be tested in a relative sense. For each plane, the velocities and accelerations revealed by the LMM system were correlated with their respective velocities and accelerations of the MA system. Table 4 presents these correlations. These results are in agreement with the acceleration and velocity figures presented earlier and show high correlation coefficient values and significance levels ($r > 0.95$, $p < 0.0001$ for all planes).

The results of the repeatability tests are shown in table 5. The low standard deviations indicate that the repeatability of the LMM was excellent.

Table 5

Repeatability of LMM range estimation. The mean (in degrees), standard deviation, minimum, and maximum are presented for each plane, ROM and asymmetry combination. The sample size was 10 for each condition.

Plane	ROM (Deg.)	Asymmetry (Deg.)	Mean	*Sd. dev.*	Min	Max
Frontal	15	0	14.38	0.07	14.30	14.53
	30	0	29.06	0.20	28.78	29.42
	45	0	41.54	0.22	41.21	41.84
	15	15	14.58	0.14	14.45	14.84
	30	15	29.98	0.21	29.58	30.20
	45	15	41.97	0.20	41.66	42.21
	15	30	15.21	0.16	15.00	15.43
	30	30	30.91	0.08	30.75	31.04
	45	30	44.31	0.34	43.84	44.82
Sagittal	15	0	14.74	0.56	13.34	15.24
	30	0	30.24	0.03	30.22	30.32
	45	0	43.93	0.82	42.96	45.28
	15	15	15.57	0.07	15.47	15.69
	30	15	31.65	0.09	31.50	31.75
	45	15	45.46	0.08	45.38	45.68
	15	30	17.09	0.25	16.71	17.43
	30	30	34.25	0.23	33.76	34.54
	45	30	48.95	0.31	48.48	49.48
Transvr.	14	0	13.45	0.61	12.92	14.33
	28	0	27.60	0.90	26.73	29.40

The repeatability did slightly vary according to the deviation from neutral. However, all deviations were well within an acceptable range.

Discussion

By comparing the ROMs given by both the MA and LMM systems with the corresponding actual ROMs, it is apparent that the LMM ROM values tended to increase slightly as asymmetry increased (for the sagittal and frontal planes only). The LMM system underestimated at 0 asymmetry, then got very close to the actual ROM at 15 degrees asymmetry, and at 30 degrees asymmetry the ROM was a little overestimated (see tables 1 and 2). The MA system tended to consistently overestimate the ROMs to a larger degree.

In order to account for the possible linear increment in ROM given by the LMM with respect to the increase in asymmetry, a correction factor can be introduced into the analysis procedure. However, the deviations reported were not alarming and could have been introduced by a combination of many factors besides the analysis procedure (experimenter error, recording error, etc.). The transverse plane ROM's for the LMM system were very close to their corresponding actual ROMs and those revealed by the MA system (see table 3). Note that the transverse plane ROMs were collected, due to setup difficulties of the MA system, without any interaction between the other two planes considered.

It is apparent that the velocities and accelerations of both systems were very comparable at most ROMs. However, in general the LMM velocities and accelerations values were lower than those of their MA corresponding values (see figures 4 through 9). This finding was expected since the MA ROMs were consistently overestimated when compared to the reference system and this overestimation could have been carried over, through numerical differentiation, to the velocity and acceleration figures. For all three planes, both systems yielded high correlation values between the corresponding velocities and between the corresponding accelerations (see table 4). This finding suggests that the LMM system estimates of velocity and acceleration are relatively consistent and at least as accurate as those of the commonly used MA system. It is difficult to conclude that the LMM tends to underestimate the velocity and acceleration since there was no reference system that both systems were compared against and due to the ROM overestimation of the MA system discussed above.

Since the LMM is a three-dimensional (3-D) system, it would be ideal to compare this system with another 3-D system of motion quantification. However, tracking motion where more than two planes are interacting is difficult to achieve with a two-dimensional (2-D) system without major apparatus modification. When using a 3-D motion tracking system it is simpler to account for interactions between the three planes described earlier.

This study has shown that the LMM system is a relatively accurate and very repeatable means to monitor motion characteristics in the workplace. This system overcomes most of the limitations of the video-based motion evaluation systems. This study shows that the relative position error is about half of that seen in the video-based system and the velocity and acceleration estimates are at least as good as the video-based systems. An added benefit of the LMM is the ease of signal processing. The position signal is differentiated and smoothed automatically to facilitate the predictions of velocity and acceleration. Hence, this system provides a reliable and quick means to monitor trunk motions in the workplace.

Perhaps one of the greatest benefits of the LMM is that it provides not only an accurate but inexpensive means of monitoring trunk motion in the workplace. Three-dimensional video-based systems can cost upwards of $100,000, whereas the LMM can be constructed relatively cheaply. In addition, high speed motions could be accurately assessed with the LMM by simply increasing the sampling rate. However, increasing the sampling rate on a video-based system would entail the purchase of high speed cameras which are extremely expensive.

A device such as the LMM can provide several types of valuable information for the assessment of the workplace. First, three-dimensional trunk posture information is available. When this posture information is used along with load moment information, a quantitative biomechanical assessment of the workplace is possible. One can more accurately determine the external moment (due to both the load and trunk center of gravity) that must be resisted in order to perform the lifting task. Since trunk strength is intricately related to trunk posture, this static posture information could be used to determine the risk of overexertion due to the work.

Second, the dynamic strength capabilities could be better assessed if one was able to document the trunk velocity characteristics associated with a task. Marras et al. (1984, 1987) have documented the manner in which the trunk strength decreases as the angular trunk velocity increases. In addition, Marras and Mirka (1989) have described how dynamic trunk strength changes as the trunk position becomes more asymmetric. The dynamic trunk motion characteristics associated with a workplace task could be documented and compared to dynamic strength capabilities to assess the risk of trunk overexertion due to dynamic lifting.

Third, the dynamic trunk motion characteristics such as angular trunk velocity and acceleration associated with a work task could be used to better predict the loading that occurs on the spine during the performance of work. Marras et al. (1984, 1986, 1990, 1991) have documented the manner in which the major muscles of the trunk behave to produce trunk symmetric and asymmetric velocities and accelerations at different trunk torque levels. This information has also been incorporated into a simulation model of trunk loading during work (Marras and Sommerich, 1991a,b). Thus, if one knows the dynamic position and motion characteristics of the trunk and the load moments that are resisted with the back, then one could predict the compressive and shear forces acting upon the spine during a work task. This information could be compared to spine loading tolerance limits to determine safe lifting limits in the workplace. A study is currently underway in the Biodynamics Laboratory at the Ohio State University that indicates how trunk motion characteristics are associated with the risk of LBD in industry.

Finally, the LMM could be used to document the reduction in dynamic motion capabilities associated with a low back disorder. Thus, patient motion component profiles, such as ROM, velocity and acceleration capabilities could be used as an indication of the extent of injury or may document when a worker is ready to return to work.

Collectively, this information has shown that assessing the dynamic motion characteristics of the trunk during the performance of work can facilitate the use of new dynamically based biomechanics research to assess the risk of LBD in the workplace. These techniques could be used for job assessment as well as work redesign purposes. It is expected that they will eventually facilitate a workplace that is safer and minimizes the risk of LBD due to the work.

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