The Effect of Task Asymmetry, Age and Gender on Dynamic Trunk Motion Characteristics During Repetitive Trunk Flexion and Extension in a Large Normal Population

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***Abstract*—Management of low back pain (LBP) has remained a major challenge to both clinical and engineering communities. With present technology, the lack of anatomical finding in a majority of LBD patients has increased the interest in objective quantification of trunk performance from all areas of rehabilitation: diagnosis, treatment, disability evaluation, return to work determination, ergonomic intervention and prevention. Different dimensions of trunk performance have been quantified with a diverse set of technologies. It is essential that a normative database be established to facilitate the use of these quantitative measures in both the ergonomics and rehabilitation fields. The present study provides a new technique to measure dynamic trunk performance characteristics during repetitive flexion and extension of the trunk at the preferred speed in a large, healthy population (N=351). The effects of task asymmetry, gender and age on these dynamic parameters were investigated. Significant results were found due to task asymmetry, age and gender on dynamic parameters of trunk performance. The higher derivative motion parameters such as velocity and acceleration were more sensitive to the main effects than the range of motion. In general, increased asymmetry and age caused diminished dynamic trunk capability. These results were compared to an industrial surveillance study that identified the injurious levels of high trunk velocity and acceleration. Clinically, these results have provided the basis for quantifying the extent of trunk dysfunction of patients with different low back disorder diagnoses.**

I. Introduction

Low back disorder (LBD) is one of the most expensive health care problems for those between the ages 20 and 50, the most expensive industrial injury, the most expensive musculoskeletal problem, and the most common cause of disability under age of 45 [1]–[5]. For 90% of LBD patients, a rapid recovery is expected since the natural history low back pain is self-limiting. In the remaining 10%, medical pathology and societal predicament combine to account for 80% of the total cost of low back pain [2], [4]-[6]. The primary prevention of low back disorders must accompany the secondary and tertiary preventions to avoid the development of chronicity of the condition that leads to significant disability and handicap. State-of-the art technology can document anatomical findings for only 10-15% of the LBD patients [7]. Hence, quantitative assessment of trunk functions in terms of strength, endurance, mobility and coordination has become imperative in the management of LBD's [8]. This new surge of interest in objective evaluation of trunk function has been driven by the needs in all areas of rehabilitation: diagnosis, treatment, disability evaluation, return to work determination, ergonomic intervention and prevention [9].

Functional capacity evaluation has predominately included either isometric trunk strength or range of motion (ROM). Strength has served as a measure of functional capacity of the trunk, determining whether one is able to perform a particular task [8], [10]–[13], and has also been used as a descriptive measure of the extent of a low back disorder (LBD) [8], [14]. Range of motion has often been used as a clinical measure to assess the status of the low back or track the progression of LBD rehabilitation. The National Institute for Occupational Safety and Health (NIOSH) has recently published a document that describes clinical tests for evaluation of the back [15]. These tests rely heavily on ROM measures. Isometric strength and ROM are not strong discriminators of normal and LBP patients. New evidence suggests that dynamic measures of low back status may be more sensitive than the traditional static measures such as ROM and isometric strength. Marras and Wongsam [16] were the first to demonstrate that trunk sagittal velocity distinguished between normal and LBD subjects better than ROM. More recently [17] has shown that three-dimensional dynamic measures of trunk velocity and angular acceleration were important in the documentation of LBD's. It has been shown that dynamic trunk performance measures are sensitive indicators of LBD [14], [18]–[20]. Significant specificity of trunk muscle recruitment has been shown in symmetric and asymmetric trunk motions [21], [22].

The purpose of the present paper is to document the motion characteristics of subjects who have not experienced a significant LBD by quantifying their dynamic trunk motion capacity;

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TABLE I
THE DEMOGRAPHIC ANTHROPOMETRIC DATA FOR NORMAL MALE AND FEMALE SUBJECTS PARTICIPATED AT DIFFERENT DECADES OF AGE

Var.	Gender	All age group	20's	30's	40's	50's	60's
No. of subjects	Male	200	71	39	39	25	25
	Female	151	47	27	26	24	27
WT(kg)	Male	81.2(14.2)	74.0(10.0)	80.2(12.8)	85.2(15.4)	89.5(14.8)	81.8(14.2)
	Female	67.4(15.9)	56.6(8.9)	61.0(10.4)	73.7(17.3)	76.9(18.0)	71.1(14.3)
HT(cm)	Male	177.7(7.2)	178.6(7.7)	179.9(7.2)	176.5(5.9)	176.8(5.9)	174.0(6.7)
	Female	163.6(6.6)	163.8(7.1)	164.3(6.0)	163.6(6.3)	164.2(8.0)	162.2(5.2)

to determine the reliability of trunk performance by testing normal subjects over five separate sessions; to determine the effects of the factors that may influence trunk motion such as gender and age. Hence, in this study we will describe the expected normal trunk motion characteristics of the trunk while taking into account the influence of task asymmetry, age and gender. This comprehensive normal database can be used as a benchmark by both clinicians and ergonomists in the evaluation of the functional capacity of the trunk and the task demands during the rehabilitation process.

II. METHODS

A. Experimental Protocol

An experiment has been developed to solicit the trunk motion characteristics or motion signature responses to sagittal bending as a function of task asymmetry. In this experiment a group of normal subjects were asked to flex and extend their trunks repeatedly in various symmetric and asymmetric planes of movement while the three-dimensional motion characteristics of the trunk were monitored. No trunk resistance or external load was applied to the trunk during these tests. During the testing session the subjects viewed a screen that indicated the instantaneous twisting (asymmetric) position of the trunk. A twisting position target (± 2 deg) was also identified on the screen. The subjects were asked to repeatedly flex and extend their trunk at their maximum preferred speed while maintaining their twisting position within the target. The transverse plane position signal from each back monitor was controlled with a comparator circuit. The comparator circuit was used as a feedback mechanism to the subject so they could control the transverse plane motion and, thus, control the asymmetric experimental conditions. If the twisting position fell outside the target during the trial a tone was automatically sounded and the trial was repeated. In this manner it was possible to monitor the free dynamic natural motion characteristics of the trunk without physically restricting or interfering with the trunk motion.

B. Subjects

The normal subject population consisted of 351 males and females between the ages of 20 and 70 who claimed to have never experienced significant back pain. The number of subjects of each gender as well as the number of subjects within each decade of age are shown in Table I. Anthropometric characteristics of these subjects are also shown in Table I.

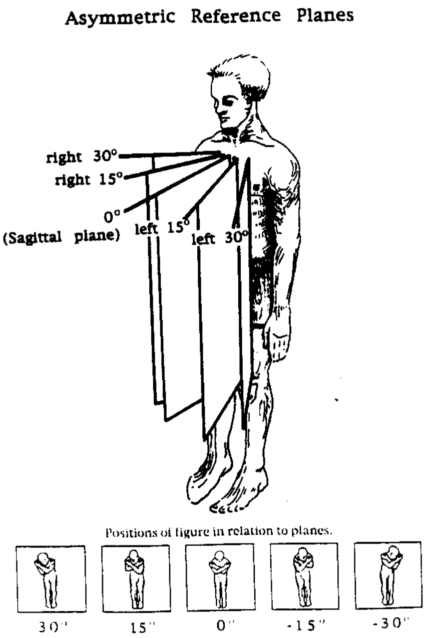

Fig. 1. The asymmetric planes defining the five levels of task asymmetry during repetitive trunk flexion and extension at maximum preferred speed.

C. Experimental Design

Five asymmetric positions of the trunk were tested in this study. Asymmetry was defined as the amount of trunk twist in the transverse plane of the body. Asymmetry was set at five levels consisting of a sagittally symmetric position (zero), 15 degrees of twist to the right (15 right), 15 degrees of twist to the left (15 left), 30 degrees of twist to the right (30 right), and 30 degrees of twist to the left (30 left). These asymmetric lines of action are illustrated graphically in Fig. 1. The initial testing position for each subject consisted of the zero condition followed by the two 15 degree conditions, followed by the two 30 degree conditions. The order of the right and left conditions were counterbalanced in the experimental design. Subjects were not always able to perform all conditions.

Twenty-six dependent variables were observed from this experiment as a function of each asymmetric condition. One variable (ability) simply described the capability of the subject to complete the various experimental conditions. It was observed that LBD patients may not be able to perform the task at the 15 and 30 degree asymmetric conditions. The second variable consisted of twisting ROM capability (not part of experimental conditions). Fourteen trunk motion characteristics or features were observed as a function of the experimental conditions. These characteristics consisted of 1) the range of motion (ROM) (difference between maximum and minimum position) in the sagittal plane, 2) ROM in the frontal plane, 3) ROM in the transverse plane*, 4) peak flexion velocity in the sagittal plane, 5) peak extension velocity in the sagittal plane, 6) peak flexion acceleration in the sagittal plane, 7) peak extension acceleration in the sagittal plane, 8) peak right lateral (frontal) bending velocity, 9) peak left lateral bending velocity, 10) peak right lateral bending acceleration, 10) peak left lateral acceleration, 11) peak right axial velocities in the transverse plane*, 12) peak left axial velocity in the transverse plane*, 13) peak right axial acceleration in the transverse plane*, and 14) peak left axial acceleration in the transverse plane*. Finally, 10 weighting coefficients were used to characterize the continuous nature of each of the angular position, velocity and acceleration profiles in the sagittal plane. These coefficients were computed based on the optimal feature extraction procedure that enabled accurate reconstructions of the continuous profiles while reducing the dimensions of the original data [23].

D. Apparatus

Many researchers have documented trunk positions using electrogoniometers [24]–[28]. However, many of these studies were unable to document trunk position in three-dimensional space and none have focused upon the evaluation of dynamic trunk motion characteristics. The trunk's three-dimensional dynamic trunk motion characteristics were monitored in this study with a triaxial electrogoniometer. This device was developed in our laboratory and is referred to as the lumbar motion monitor (LMM). This device has been validated [29] and was used to document trunk motions used by workers in industry [30]. The LMM is essentially an exoskeleton of the spine that has been instrumented with a series of potentiometers to document the three-dimensional position in space of the thoraco-lumbar spine. The LMM is attached via a harness system to the thorax and the pelvis with a pre-molded semi-rigid plastic material (Orthoplast). This provides two stable "anchors," at the midspine (thorax) and at the pelvis. Thus, the LMM measures the difference in trunk position of primarily the lumbar spine (as a unit) relative to the pelvis. The LMM is shown on a subject in Fig. 2.

The LMM signals were sampled at 60 Hz via an analog-to-digital converter and a portable 386-based microcomputer. After the data were collected, the signals were processed in the laboratory to determine the position, velocity, and acceleration of the trunk as a function of time in the sagittal, frontal (lateral), and transverse (axial twisting) planes of the body. Voltage readings from the potentiometers are converted into angular position in the cardinal planes using a regression (calibration) model (R^2 = 0.978 sagittal, 0.976 lateral, 0.983 twisting). The angular velocity and acceleration were obtained through numerical differentiation. Filtering (to eliminate noise) was also performed prior to differentiation of the signal. Our validation study [29] indicated that the LMM's ability to measure trunk position velocity and acceleration in three-dimensional space is more consistent than video-based systems.

*These motion characteristics were limited by the experimental conditions.

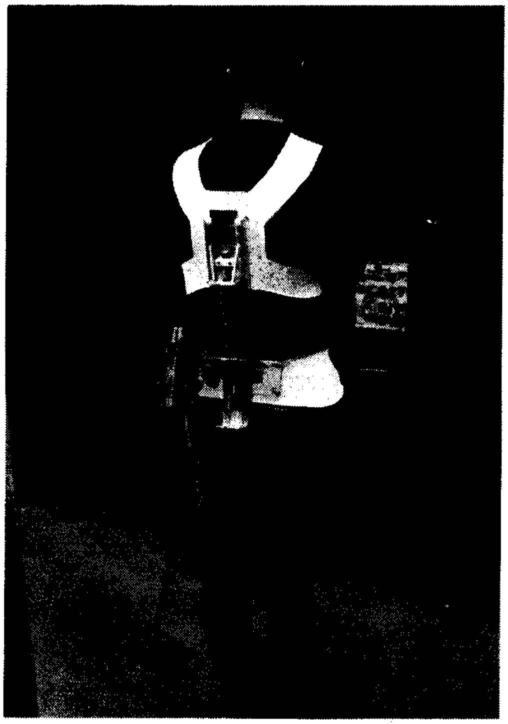

Fig. 2. The Lumbar Motion Monitor (LMM) measuring three dimensional trunk motion and the oscilloscope providing feedback about the trunk axial rotation during repetitive trunk flexion and extension at maximum preferred speed.

TABLE II
THE DEMOGRAPHIC ANTHROPOMETRIC DATA FOR NORMAL MALE AND FEMALE SUBJECTS PARTICIPATED IN RELAIBILITY TEST

Gender	No. of subject	WT (kg)	HT(cm)	Age
Male	10	76.4(9.0)	180.4(9.4)	27.1(6.3)
Female	10	54.3(6.3)	162.0(8.1)	27.0(6.3)

E. Measurement Reliability

In order to assess the repeatability and reliability of the LMM testing protocol an initial study was performed. Twenty normal subjects, ten males and ten females, performed the experimental protocol on five separate testing occasions with a one week period separating each testing session (Table II). The trunk motion characteristics in the sagittal and frontal planes were compared over the five testing periods. There were no statistically significant differences among the trunk motion characteristics between the five testing sessions (MANOVA, $p > 0.05$). Reliability analysis were performed and the Cronbach Alpha correlation coefficients were computed to assess the repeatability of the parameters over the five sessions (Table III). These correlations were higher for sagittal plane trunk motion characteristics than the frontal plane parameters. The high correlations of dynamic motion characteristics indicate their stability and strong reliability. Hence, they can be used as indicators of the functional status of the neuromuscular spine system in normal subjects.

F. Procedure

Subjects were permitted to become familiar with the visual display representing the transverse plane trunk position. The

TABLE III
CRONBACH ALPHA CORRELATION COEFFIENTS FOR ALL 20 REPEATABILITY SUBJECTS ON MOTION PARAMETERS AT ALL FIVE TASK ASYMMETRIES, CONTINUOUS PARAMETERS AT TASK ASYMMETRY ZERO, AS WELL AS ADDITIONAL MOTION PARAMETERS

	Task Asymmetries					Continuous Parameters at Task Asymmetry Zero			
Motion Features	Zero	15 Right	15 Left	30 Right	30 Left	Continuous Parameters	Position	Velocity	Acceleration
Sagittal ROM	.96	.91	.90	.94	.95	1	.94	.95	.95
Sagittal Flexion Velocity	.96	.94	.93	.95	.95	2	.77	.80	.85
Sagittal Extension Velocity	.95	.94	.93	.95	.95	3	.78	.84	.88
Sagittal Flexion Acceleration	.95	.95	.94	.94	.95	4	.87	.86	.93
Sagittal Extension Acceleration	.95	.96	.95	.93	.95	5	.76	.72	.77
Lateral ROM	.88	.72	.89	.47	.89	6	.73	.13	.91
Lateral Right Velocity	.92	.62	.87	.57	.89	7	.82	.78	.89
Lateral Left Velocity	.91	.65	.84	.73	.93	8	.72	.29	.87
Lateral Right Acceleration	.92	.65	.86	.72	.83	9	.82	.33	.89
Lateral Left Acceleration	.91	.61	.88	.78	.87	10	.69	.57	.79
Additional Motion Features									
Twist position right						1.00			
Twist position left						1.00			
Twisting range						1.00			
Ability						1.00			

TABLE IV
STATISTICAL SUMMARY SHOWING EFFECT OF ASYMMETRY, GENDER, AND AGE ON MOTION VARIABLES OVER ALL ASYMMETRIC CONDITIONS. EACH INDIVIDUAL PLANE WAS EVALUATED VIA ANOVA

PLANE	DIREC-TION	MOTION VAR.	ASM	GENDER	AGE	GENDER by AGE
		ALL VAR'S (MANOVA)	**	**	**	**
SAGITTAL		RANGE (degree)	**	**	**	**
	FLEX.	VELOCITY (deg/sec)	**	**	**	**
	EXTEN.	VELOCITY (deg/sec)	**	**	**	*
	FLEX.	ACC. (deg/sec^2)	**	**	**	*
	EXTEN.	ACC. (deg/sec^2)	**	**	**	
FRONTAL		RANGE (degree)	**			
	RIGHT	VELOCITY (deg/sec)	**		**	
	LEFT	VELOCITY (deg/sec)	**		**	
	RIGHT	ACC. (deg/sec^2)	**		**	
	LEFT	ACC. (deg/sec^2)	**		**	
TRANSVERSE		RANGE [1] (degree)	**	*		**
	CW[2]	VELOCITY (deg/sec)	**	**	**	*
	CCW[3]	VELOCITY (deg/sec)	**	**	**	
	CW	ACC. (deg/sec^2)	**		**	
	CCW	ACC. (deg/sec^2)	**	*	**	

** Significant effect ($P<0.001$)
* Significant effect ($P<0.01$)
1 Controlled range of motion
2 Clockwise
3 Counterclockwise

TABLE V
STATISTICAL SUMMARY SHOWING EFFECT OF GENDER AND AGE ON MOTION VARIABLES ACROSS ASYMMETRIC CONDITIONS. EACH INDIVIDUAL PLANE WAS EVALUATED VIA ANOVA

PLANE	DIREC-TION	MOTION VAR.	0 ASYMMETRY			15 ASYMMETRY			30 ASYMMETRY		
			GEN-DER	AGE	GEN. by AGE	GEN-DER	AGE	GEN. by AGE	GEN-DER	AGE	GEN. by AGE
		ALL VAR'S (MANOVA)	**	**		**	**	*	**	**	**
SAGITTAL		RANGE (degree)	**		*	**	**	**	**	**	
	FLEX.	VELOCITY (deg/sec)	**	**		*	**	*		**	
	EXTEN.	VELOCITY (deg/sec)	**	**		*	**			**	
	FLEX.	ACC. (deg/sec^2)	**	**		*	**			**	
	EXTEN.	ACC. (deg/sec^2)	**	**		**	**			**	
FRONTAL		RANGE (degree)									
	RIGHT	VELOCITY (deg/sec)					**			**	
	LEFT	VELOCITY (deg/sec)					*			*	
	RIGHT	ACC. (deg/sec^2)		*			**			**	
	LEFT	ACC. (deg/sec^2)		**			**			**	
TRANSVERSE		RANGE [1] (degree)				*		*			
	CW[2]	VELOCITY (deg/sec)				*	**	*		**	
	CCW[3]	VELOCITY (deg/sec)				**	**			**	
	CW	ACC. (deg/sec^2)		**			**			**	
	CCW	ACC. (deg/sec^2)		**		**	**			**	

** Significant effect ($P<0.001$)
* Significant effect ($P<0.01$)
1 Controlled range of motion
2 Clockwise
3 Counterclockwise

subject was instructed to twist so their transverse plane position dot moved within the target zone. Subjects were given six instructions. These consisted of 1) cross their arms in front of their chest, 2) stand with their feet shoulder width apart and keep them in the same location for all conditions, 3) flex and extend their trunks repeatedly in the sagittal plane as fast as they can comfortably while keeping the transverse plane position dot between the target zone dots, 4) watch the dots at all times during testing, 5) if their transverse plane position fell outside the target zone a tone would sound and the trial would be repeated, and 6) move continuously until instructed to "relax." Data were collected up to 8 seconds for each experimental run.

G. Data Analysis

Custom software developed in the Biodynamics Laboratory converted the electrical signal from each back monitor into trunk position, velocity and acceleration. The software program graphically displays trunk positions in each plane of the body separately and permits analization of each motion component independently throughout the exertion. The first entire cycle (flexion and extension) during each trial was considered a warm-up motion and was discarded for analysis purposes. The following four flexions were analyzed and

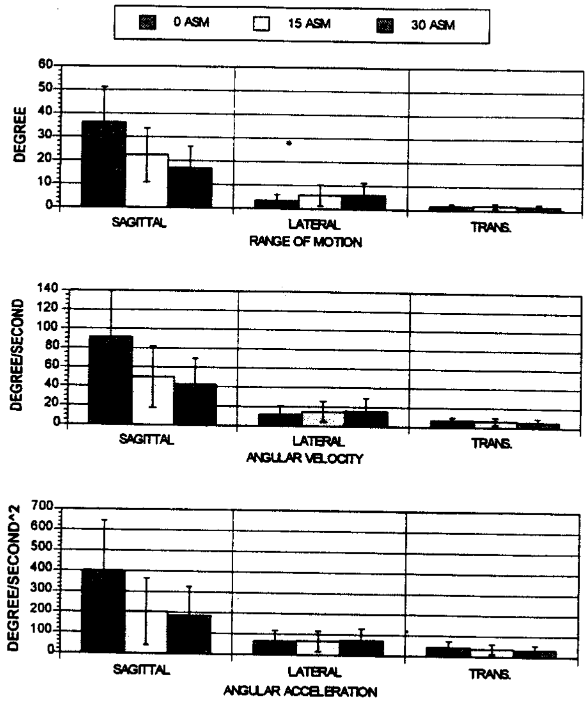

Fig. 3. Dynamic Trunk Motion Characteristics in Different Asymmetric Conditions for 351 Normal Subjects.

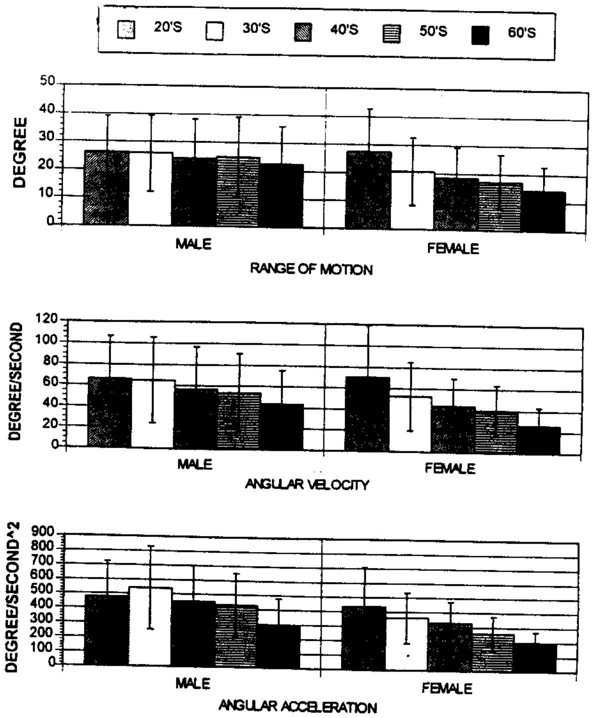

Fig. 4. Sagittal dynamic trunk motion characteristics of normal subjects ($N = 351$) as a function of gender and age categories over all asymmetric conditions.

averaged. Then the four matching extensions were analyzed and averaged. This process was completed for each plane of the body. The analysis program computed the trunk motion characteristic variables discussed earlier.

The feature extraction from the continuous movement patterns required the following data processing. The middle three cycle of movements were interpolated and averaged into 128 data points, thus the data were normalized with respect to cycle time and allowed between individual comparison. Data matrices consisted of the 351 columns (number of subjects) and 128 rows (number of data points for each subject's continuous profile; i.e., position, velocity and acceleration). The eigenvalue and eigenvectors of the correlation matrix of the subjects data matrices were computed by singular value decomposition (SVD) algorithm using MATLAB (MathWorks, Inc. Natick, MA. 01760). The eigenvectors represent the principal patterns (bases) and cumulative sum of the eigenvalues reflect the amount of explained variability of the original data matrix. Using the original data matrices and the eigenvectors, the weighting coefficient matrices were computed. Inspection of eigenvalues indicated that the first five eigenvectors explained more than 97% of variability of the original data. The first ten weighting coefficients were used to reconstruct the original movement profiles. Hence, representation of the continuous patterns of motion was achieved with a significant reduction in the dimension of the original data (from 128 data points to 10 coefficients). A more detailed description of the method is provided in [23].

The trunk motion characteristics were first analyzed by descriptive statistics in terms of the decade of age and gender. The main effects of task asymmetry, age and gender and their interaction effects were determined by the MANOVA. The multiple comparison of means of the variable that were significantly affected were performed by Tukey tests.

III. Results

The results of MANOVA and ANOVA for the effects of task asymmetry, age and gender on the dynamic motion characteristics are shown in Table IV. The effect of task asymmetry was significant for all the motion parameters (Table IV and Fig. 3). This table indicates that age and gender as well as their interaction affect the motion characteristics in the sagittal plane. Age alone affects all trunk motion characteristics other than range of motion in the lateral and transverse planes. Motion parameters in the transverse plane are selectively affected by age and gender. However, one must note that this plane of motion was controlled by the experimental conditions. Table IV shows a significance summary for these same parameters for each of the task asymmetries. For the sagittal symmetric condition, all motion parameters were affected by main effects of gender and age exclusively. However in the lateral and transverse planes only acceleration was affected by age. As the task asymmetry increased, the number of motion parameters that were affected by age increased with the exception of non-sagittal range of motion. The largest number of trunk motion characteristics effected by gender were found at the 15 degree asymmetry condition.

Table V summarizes the significant influence of asymmetry upon the motion characteristics as a function of gender and age. Descriptive statistics indicating the mean and standard deviation for all trunk motion parameters in the three planes of motion as a function of age and gender are shown in Table

TABLE VI

MEAN (STANDARD DEVIATION) TRUNK MOTION CHARACTERISTICS OF THE NORMAL SUBJECTS SHOWN AS A FUNCTION OF GENDER AND AGE (0 ASMMETRY). ANY MOTION CHARACTERISTICS OF LBD PATIENTS CAN BE NORMALIZED BY DIVIDING THE MEASURED VALUE BY THE AGE AND GENDER MATCHED MEAN VALUE REPORTED IN THIS TABLE

PLANE	DIRECTION	MOTION VAR.	AGE									
			MALE					FEMALE				
			20's	30's	40's	50's	60's	20's	30's	40's	50's	60's
SAGITTAL		RANGE (degree)	38.71 (14.41)	41.47 (13.57)	40.97 (14.35)	42.76 (16.58)	37.60 (15.54)	38.64 (17.04)	31.81 (12.82)	28.85 (10.61)	26.47 (7.72)	23.88 (9.46)
	FLEXION	VELOCITY (deg/sec)	104.12 (51.98)	113.88 (49.86)	102.63 (47.15)	101.75 (49.38)	80.25 (45.51)	100.02 (53.74)	83.31 (37.71)	70.85 (28.73)	61.62 (19.54)	47.91 (15.87)
	EXTENSION	VELOCITY (deg/sec)	106.54 (48.09)	120.94 (53.82)	109.58 (44.01)	105.16 (46.26)	81.99 (42.88)	104.50 (53.43)	91.81 (39.96)	76.63 (29.35)	67.79 (22.14)	49.64 (18.38)
	FLEXION	ACC. (deg/sec^2)	475.49 (250.44)	541.90 (287.85)	450.09 (248.38)	425.40 (222.40)	299.02 (181.32)	435.59 (270.85)	359.98 (175.65)	327.45 (144.80)	257.09 (117.98)	194.71 (72.27)
	EXTENSION	ACC. (deg/sec^2)	490.93 (269.25)	552.06 (302.13)	469.26 (248.04)	417.55 (206.49)	322.76 (264.20)	445.10 (248.90)	375.13 (187.90)	309.93 (163.54)	291.78 (146.52)	188.36 (90.72)
LATERAL		RANGE (degree)	3.72 (3.22)	4.25 (3.70)	3.26 (2.55)	3.74 (2.77)	2.69 (1.59)	2.95 (2.05)	3.27 (3.56)	2.71 (1.46)	2.87 (1.61)	2.67 (1.86)
	RIGHT	VELOCITY (deg/sec)	13.27 (9.32)	14.18 (12.08)	10.80 (8.49)	12.48 (8.33)	9.50 (8.47)	10.58 (6.04)	12.94 (13.83)	10.51 (8.02)	9.95 (5.93)	7.62 (3.85)
	LEFT	VELOCITY (deg/sec)	13.29 (10.61)	15.49 (13.66)	10.87 (7.95)	12.73 (8.02)	9.44 (8.22)	12.72 (12.37)	11.67 (11.58)	10.83 (7.07)	9.83 (4.83)	8.20 (4.57)
	RIGHT	ACC. (deg/sec^2)	79.57 (48.73)	68.57 (48.62)	54.91 (35.88)	63.94 (48.83)	54.92 (55.15)	89.78 (58.14)	72.44 (72.35)	56.74 (68.08)	50.39 (31.70)	45.24 (22.42)
	LEFT	ACC. (deg/sec^2)	81.76 (54.89)	72.33 (43.55)	53.37 (32.36)	59.61 (39.99)	49.03 (40.13)	96.51 (74.03)	61.02 (58.75)	59.23 (57.21)	52.26 (25.98)	46.31 (28.48)
TRANSVERSE		RANGE (degree)	1.79 (0.80)	1.50 (0.72)	1.80 (0.94)	1.96 (0.86)	1.81 (0.83)	1.73 (0.71)	1.47 (0.66)	1.51 (0.56)	1.41 (0.70)	1.80 (0.73)
	CW	VELOCITY (deg/sec)	7.87 (3.82)	6.90 (3.85)	6.38 (2.96)	7.03 (3.37)	6.08 (2.66)	6.74 (2.41)	6.09 (2.79)	5.74 (1.94)	5.38 (3.27)	6.06 (3.05)
	CCW	VELOCITY (deg/sec)	7.71 (5.44)	6.91 (3.56)	6.55 (3.28)	6.63 (3.64)	6.06 (3.19)	6.66 (2.53)	6.10 (3.33)	5.81 (2.38)	5.02 (2.82)	6.01 (4.36)
	CW	ACC. (deg/sec^2)	57.44 (35.20)	47.66 (35.91)	36.28 (18.35)	36.44 (16.04)	31.85 (14.45)	60.74 (41.72)	51.73 (41.53)	32.44 (14.16)	25.84 (11.64)	37.12 (25.97)
	CCW	ACC. (deg/sec^2)	61.36 (48.40)	46.55 (36.90)	37.55 (20.78)	33.38 (16.55)	36.74 (22.27)	59.62 (41.95)	38.53 (20.74)	35.21 (13.41)	24.34 (10.34)	35.78 (29.91)

VI for the sagittally symmetric condition. The descriptive data for 15 and 30 degree asymmetry conditions are available from the authors upon request. Generally, the motion parameters decreased with age and females typically displayed lower values than males. The mean and standard deviation for the various sagittal plane motion characteristics is presented in Fig. 4 averaged over all task asymmetries as a function of age and gender for this subject population.

IV. DISCUSSION

In this study we have been able to quantify the trunk motion characteristics of a population of normal adults with a tri-axial goniometer that can accurately measure the ROM, velocity and acceleration of the trunk in three-dimensional space. This system efficiently measures trunk motion and controlls asymmetery by requiring the subject to wear the LMM goniometer which is interfaced with an oscilloscope screen that provides feedback during the performance of symmetric or asymmetric flexion and extension tasks. Such a test would not be feasible with video-based evaluation systems which require extensive, time consuming calibration and processing. It would also be difficult to provide instantaneous feedback to the subject with such a system. Therefore, it would be difficult to control the asymmetric angle within the tolerances used in this study. This feature of our method also enhances the possibility of incorporating biofeedback in the rehabilitation of the LBD patients. Reference [25] has used a technology based on magnetic fields to study the normal patterns of trunk motion. Their significant contributions were limited to trunk angular position and subjects were not stressed in terms of their movement time. Hence, the results of the present study are unique in elliciting the preferred maximum trunk speed without any pelvic restraint or external resistence [20].

These findings have shown that it is possible to characterize the symmetric and asymmetric bending motions of a population of normal (uninjured) males and females. In general, we have observed that ROM, velocity and acceleration in the sagittal plane decrease with increasing task asymmetry (Fig. 3). However, more pronounced changes occur with asymmetry in terms of velocity and acceleration compared to ROM. This illustrates that these dynamic parameters are more robust indicators of the trunk's musculoskeletal status. It is hypothesized that trunk motion characteristics or the profile or "signature" of motion contain a large amount of information about the status of the trunk's musculoskeletal control system. Since trunk motion requires the recruitment and coactivation of the various trunk muscles, it is suggested that the trunk motion signature represents a concise summary of musculoskeletal capacity. The documented changes in recruitment strategies of trunk muscles during asysmmetric conditions may contribute to a reduced range of motion as well as a reduction of the dynamic motion characteristics as the flexion/extension task becomes more asymmetric [21], [22]. Alteration in the stress/strain distribution in the passive tissues such as additional strains in the annulus fibers and contacts between facets may also contribute to reduced motion at higher asysmmetric conditions. We have also observed that all the trunk motion components vary as a function of gender and age. In general, advancing

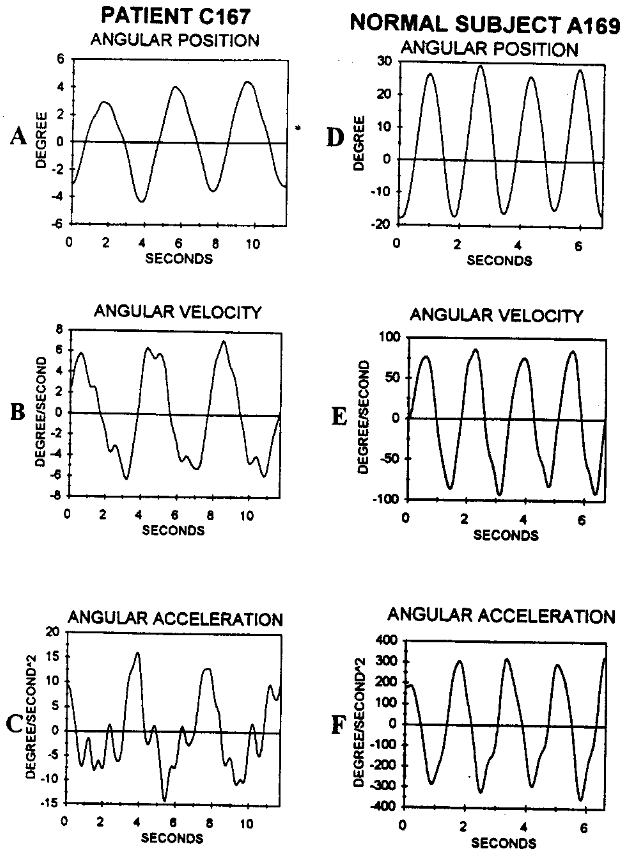

Fig. 5. The middle three cycles of sagittal dynamic trunk motion profiles of a typical low back disorder patient and a normal subject. Patient has a reduced motion capability and less smooth profile than normal subject.

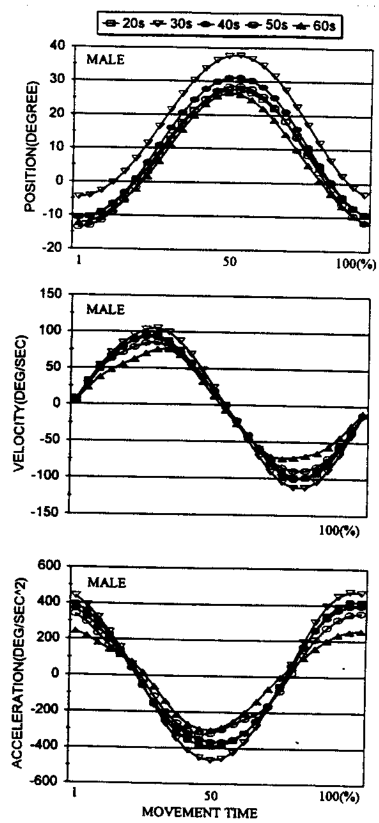

Fig. 6. The average ensemble sagittal dynamic trunk motion profile for the five age categories of normal males during sagittal symmetric task. The number of subjects in each category is shown in Table I. The normal band (+ one standard deviation) Is skipped for the purpose of clarity.

age reduces the magnitude of the measures (Fig. 4). Females also displayed a varying amount of reduction in magnitude of the measures relative to males (Fig. 4, Table VI).

For illustrative purposes the trunk motion profiles of one normal subject and one LBP patient are depicted in Fig. 5. It can be seen that the normal subject's range of motion is greater, while the patient's motion is much less smooth and contains more high frequency content. The magnitude of the velocity and acceleration of the patient were also much lower than the normal subject. The mean continuous profiles of normal males and females in the symmetric condition are presented in Figs. 6 and 7, respectively. The normal band of the normal ensemble was not depicted for the purpose of clarity. It should also be indicated that these ensembles are averaged over the whole group population, hence they are much smoother than any of the individual profiles as depicted in Fig. 5.

The test-retest reliability of trunk performance in normals has been established here based on high ICC observed over the five seperate sessions. To establish the reproducibility of the movement profiles, we also computed the variance ratio (VR) for the middle three cycles of each dynamic parameter based on Hershler and Milner [31]. The VR has a range of 0 to 1, indicating absolute reproducibility and randomness, respectively. Fig. 8 indicates the VR for the 0 sagittal symmetric condition for the males (N = 200) and females (N = 151) participating in the main study. MANOVA indicated that the effect of age was not significant, while females had significantly less reproducible angular position, velocity and acceleration profiles ($p < 0.003$). In comparison with the VR of LBD patients in our previous study [17], the normals had significantly more reproducile motion profiles than the patients ($p < 0.03$).

The cursory comparison of Figs. 6 and 7 indicates that the coordination strategies used are captured more completely by parameterising the continuous patterns of motion. This was achieved by reducing the dimensions of the original data using only the ten coefficients extracted as feature parameters. The interaction effects of age and gender were significant for all sagittal plane motion parameters with the exception of the extension acceleration, while they were not significant for any of the frontal plane motion parameters (Table IV). Aging has a more significant effect for females than males on dynamic parameters (Figs. 4, 6–7).

The clinical utility of the results has been suggested by successful identification of the LBD patients ($N = 171$) and normals ($N = 339$) in a recent study [17]. Based on the features extracted from dynamic movement profiles, we were able to develop discriminant functions to correctly classify 93.5% of normal subjects and 80% of LBD patients [17]. In addition, the extent of dysfunction in trunk muscle performance was quantified for the 10 categories of LBD patients studied. For example, from the 30 patients with

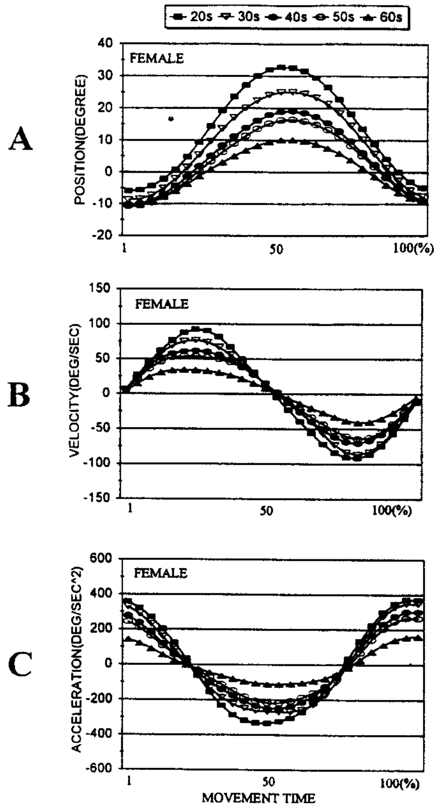

Fig. 7. The average ensemble sagittal dynamic trunk motion profile for the five age categories of normal females during sagittal symmetric task. The number of subjects in each category is shown in Table I.

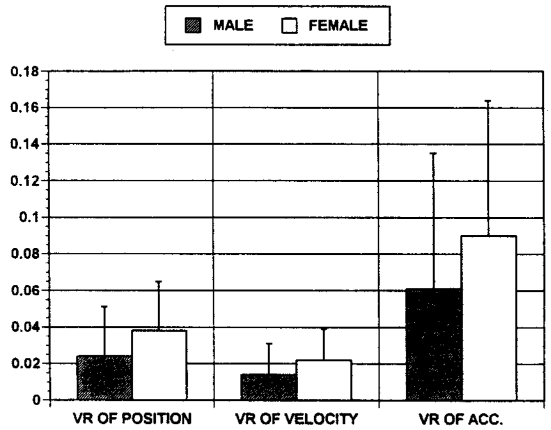

Fig. 8. The Variance Ratio (VR) computed based on [31], for the Sagittal Dynamic Motion Profiles During Asymmetric Condition for the Normal Males (N = 200), and Females (N = 151). The VR ranges from 0 to 1, Representing Absolute Reproducibility and Randomness Respectively. * Note: These motion characteristics were limited by the experimental conditions.

disc herniation (documented by their imaging studies) and pain level greater than 3 (based on 0-10 visual anolog pain scale) only 60% and 13% were able to perform the 15 and 30 degree asymmetric conditions, respectively. The ROM, extension velocity and acceleration of these patients in a sagittal symmetric task was 78%, 43%, and 31% of the age and gender controlled performances of the normals, respectively. This study also found the velocity and acceleration parameters to be more sensitive discriminators of the normal and LBD patients. This is in agreement with the present results that indicated significantly more effect of asymmetry and age on these dynamic measures than on ROM.

The following data provide an objective goal for the clinicians and patients in the design of an optimal rehabilitation program. The real-time feedback capability can allow clinicians to present the normal profiles (mean with one standard deviation) controlled for age and gender effects, as a reasonable target of their functional restoration. It is known that programs that allow pain or patient limits on the intensity and duration of the exercise or work hardening protocol are not as effective as those that present the patient with short term (within session) and long term (final) goals [32]. Rehabilitation programs to restore the normal dynamic motion characteristics should be recommended judiciously to exclude patients whose clinical conditions contraindicate such a treatment. The presented benchmark also unifies the goals and objectives of the multidisciplinary groups (physicians, behavioral and physical therapists, rehabilitation engineers, ergonomists, personnel and management representatives) that are involved in different phases of the rehabilitation process. It also yields another patient-related outcome parameter that could be used for meta-analysis and evaluation of different prevalent modes of conservative and surgical techniques to manage LBD's.

This study has described the distribution of the unconstrained and unloaded trunk motion characteristics that could be reasonably expected from the general population. These findings have important ergonomic implications for designing workplaces that consider the population's trunk bending capabilities. In addition, these results may have important implications for matching individual capabilities to the demands of the work. The latter would be necessary for considering rehabilitative progress during return to work as well as compliance to the Americans with Disabilities Act [ADA] (1991). Ergonomics assumes that the workplace can be designed so that the task demand is within the physical capabilities of most of the general population. We have seen no data base as comprehensive as the one provided here that describes the trunk motion capabilities of the normal population. This large normative data base describes the spectrum of trunk bending characteristics that would be expected at the various trunk asymmetries dictated by task design. Thus, an ergonomist would be able to consider trunk motion and subsequent risk of LBD given these additional trunk motion parameters [30].

These concepts are illustrated by the following example based on our previous models for predicting the LBP risk of industrial tasks based on the dynamic kinematic and kinetic task demands [30]. The three dimensional dynamic trunk movements in 48 companies for 403 industrial tasks were collected. The high and low risk jobs were classified based on their injury rates. The sagittal ROM, maximum velocity and acceleration in high risk groups were 31.5 (15.6) degree, 55 (38) degree/sec, 317 (225) degree/sec^2, while the respective values for the low risk group were 23.8 (14.2) degree, 39 (27) degree/sec, 226 (174) degree/sec^2. Based on the present data (Table 6), it is clear that the required trunk motion characteristics in the high risk group may be more than the capability of normal population. The probability of this mismatch increases as the task becomes more asymmetric, and an older or female worker is considered (Figs. 3 and 4). As more data becomes available about three dimensional trunk kinematic task demands, the functional trunk motion capability profiles as presented here could assess the risk of low back injury and recommend appropriate task or work place redesign to curtail the amount of mismatch that could lead to LBD's.

This data base is also valuable for rehabilitative purposes. Once the trunk motion characteristic requirements of an industrial task are known, one could use the LMM to measure the current trunk motion capability of the worker who is recovering from a LBD. By using a subject testing feedback system similar to that used in this study, an LMM test could be constructed to test the trunk's path of motion required to perform the specific industrial task. Hence, this procedure permits one to quantitatively document the ability of the patient relative to the task requirements in terms of dynamic trunk motion capabilities, which we have shown to be the most sensitive measures of trunk musculoskeletal status. This would provide an objective means of minimizing the risk of exacerbating a patient's LBD through return to work efforts. It would also provide objective quantifiable documentation relative to whether a task was designed so that the majority of the population could perform the task and, furthermore, would provide objective evidence as to how difficult it would be to accommodate someone with a LBD disability. Hence, this technique would provide the objective quantifiable measure needed for the enforcement of ADA legislation. The following data base, in conjunction with the risk analysis model [30], allow the identification of the most cost effective "reasonable accomodation" in hiring individuals with back disability.

V. Conclusion

Management of low back pain (LBP) has remained a major challenge to both the clinical and engineering communities. Lack of anatomical finding in a majority of LBP patients has increased the interest in objective quantification of trunk performance from all areas of rehabilitation: diagnosis, treatment, disability evaluation, return to work determination, ergonomic intervention and prevention. The present study provides a large normative data base (N=351) of the dynamic trunk performance characteristics during repetitive flexion and extension of the trunk at a preferred speed at five different task asymmetric conditions. These parameters were proven reliable over a five-session repeatability test. The effects of task asymmetry, gender and age on these dynamic parameters were investigated. Significant effects were found due to task asymmetry, age and gender on dynamic parameters. The higher derivative motion parameters such as velocity and acceleration were more sensitive to the main effects than the range of motion. In general, higher asymmetry and age caused diminished dynamic trunk capability. The continuous profiles of patterns of trunk movement capture significantly more information about the neuromuscular state of the spine than static ROM measurements currently used for disability assessment. The ergonomic and clinical utilities of this data base have been illustrated.

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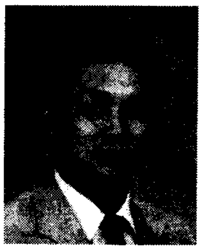

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