COMPRESSION AND SHEAR LOADS ON LUMBAR SPINE MOTION SEGMENTS IN NEUTRAL AND FLEXED POSTURES

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ABSTRACT

An analysis was performed to estimate compression and shear loads on three motion segments of the lumbosacral spine in neutral and flexed torso postures. 87 lifting tasks were evaluated using a biodynamic lifting model for lifts starting at 0, 22.5 and 45 degrees torso flexion. Results indicated that the compressive loading on the L5-S1 disk in the 22.5 and 45 degree torso flexion conditions were approximately double and triple those observed in the 0 degree condition. Shear reaction forces acted anteriorly in neutral and moderate flexion, but acted posteriorly in full flexion. Load rates were also dramatically affected by posture, with the load rate in the fully flexed posture being seven times greater than in the neutral posture. Analysis of the upper lumbar levels (L1-L2 and L3-L4) suggested significant shear forces; however, shear forces at L5-S1 remained moderate in all conditions. Results of this analysis will be used in a study examining the fatigue failure of lumbar motion segments when subjected to loads experienced at different angles of torso flexion.

1. INTRODUCTION

If one is interested in failure mechanisms of the lumbar spine resulting from mechanical overload experienced in lifting activities, it is important to understand how loads on the spine are affected by the posture adopted by the torso.

The present authors were interested in establishing dynamic loading profiles for motion segments of the lumbar spine at different angles of torso flexion during common lifting tasks. The ultimate purpose of this analysis was to develop loading estimates that could be used in fatigue testing of lumbosacral motion segments so that the effects of torso flexion on the number of cycles to failure could be determined.

To achieve this goal, it was necessary to establish: (1) compression and shear loads acting at L5-S1 in neutral (0 degrees torso flexion), 22.5 degrees lumbar flexion, and 45 degrees of lumbar flexion (using the OSU biodynamic model), (2) the resultant force vector in the sagittal plane, (3) the orientation of the superior endplates of the lumbar and sacral vertebral bodies *in vivo* in the three orientations described above, and (4) translation of the resultant force vector to the upper lumbar motion segments (L3-L4 and L1-L2) to determine the compressive and shear components of the resultant given the orientation of segments in the various postures.

2. METHOD

2.1 Development of Loading Profiles at L5-S1 at Torso Flexion Angles of 0, 22.5 and 45 Degrees

Loading profiles for lifting tasks initiated at 0, 22.5 and 45 degrees of trunk flexion were estimated using an EMG-assisted biomechanical model which has been under development in the Ohio State University Biodynamics Laboratory over the past 18 years (Marras and Reilly 1988, Marras and Sommerich 1991a, b, Marras and Granata 1997). This model provides estimates of spine loading parameters based upon measured activity of ten trunk muscles, from which estimates of muscle force and subsequent spine loading are determined.

A database of sagittal lifting tasks from a previous study was used to obtain estimates of compression, shear, and rates of loading on the L5-S1 joint when performing lifts initiated at trunk flexion angles of 0, 22.5, and 45 degrees using the Lumbar Motion Monitor (LMM). The data used for this analysis consisted of both symmetric and asymmetric tasks; however, only data from symmetric lifts were used in the analysis. Boxes weighing from 4.5 – 11.2 kg were lifted from several different heights (floor, knee level, waist level), requiring varying degrees of torso flexion by the study subjects. A sample of 27-31 lifts starting at each of 0, 22.5 and 45 degree torso flexion angles was obtained and analyzed to establish compression, shear, and load rates using this model. Lifting trials were included in this analysis if they started within 2 degrees of the desired trunk flexion angle, as calculated by the OSU Biodynamics Model. The compression, shear and load rates obtained in this analysis were taken at the point of peak sagittal plane resultant force acting on the spine during the lift.

2.2 Determination of the Orientation of L2, L4, and S1 Superior Endplates in Neutral and Flexed Torso Postures

The orientation of the lumbar and sacral vertebrae in various levels of trunk flexion was determined using data provided by Chen (2000). Regression equations (both linear and exponential) were utilized by Chen (2000) to predict superior endplate inclinations of the lumbosacral vertebrae as a function of torso flexion throughout the range studied. Prediction equations provided excellent fits to the data, with all six prediction equations having R^2 values of greater than 0.95. It was found that the upper levels (L1-L3) were well described by linear equations, while the lower levels (L4-S1) were best described by exponential fits. For the purposes of the current investigation, superior endplate angles were required for L2, L4, and S1 at torso flexion angles of 0 degrees, 22.5 degrees, and 45 degrees. Chen (2000) provided data on superior endplate angles derived from radiographic measurement at 0 degrees torso flexion, and these were used as provided. Superior endplate angles for L2, L4, and S1 at 22.5 and 45 degrees of torso flexion were obtained through the use of the regression equations developed by Chen (2000).

2.3 Procedure for Estimation of Compression and Shear Forces at L1-L2 and L3-L4 at 0, 22.5 and 45 degrees of Torso Flexion

It should be noted that the OSU Biodynamics Model was designed to provide estimates of forces and moments only at the lumbosacral junction. However, for the current analysis, estimates of compression and shear forces were desired for levels L1-L2 and L3-L4, as well. Since no direct estimation could be made using this model, a simplifying assumption was made that the magnitude and direction of the loads and the rate at which loading was experienced at L1-L2 and L3-L4 were equivalent to that experienced at L5-S1. While it must be acknowledged that the loads on middle and upper levels of the lumbar spine are somewhat less than those at the lumbosacral joint, the difference is generally considered to be fairly small (Chaffin et al. 1999). Once the compression and A-P shear forces were calculated at L5 –S1, and a sagittal resultant vector magnitude and angle calculated, the vector was translated to the superior endplates of L2 and L4 to estimate the relative compression and shear forces acting on the upper lumbar levels. These calculations of compression and shear forces at the upper lumbar levels were based upon the magnitude and direction of the vector calculated at L5-S1, and the orientation of the vertebrae at the upper levels of the lumbar spine, as calculated from the data provided by Chen (2000).

3. RESULTS

3.1 Results of Analysis of Lumbosacral Loads at Three Levels of Torso Flexion

Table 1 contains results of the analysis of loads on the lumbosacral joint for lifts initiated at three torso angles (0, 22.5, and 45 degrees of flexion), as predicted by the OSU biodynamic model. As can be seen from this table, the predicted compression and resultant forces in the 22.5 and 45 degrees torso flexion are approximately double and triple those observed in the neutral posture, respectively. Shear reaction forces at L5-S1 are directed anteriorly in the neutral and in mid-flexion postures, but are directed posteriorly in the fully flexed torso posture. The averaged peak loading rates on the lumbosacral joint were also dramatically affected by posture, being approximately 650 N/s in the neutral posture, but as high as 4650 N/s in the fully flexed posture. Since the lumbosacral spine, like most biological materials, is viscoelastic in nature, the change in loading rates will greatly impact the response of the spine to compressive and shear loads.

3.2 Results of the Analysis of the Orientation of the Lumbosacral Spine in Neutral and Flexed Postures

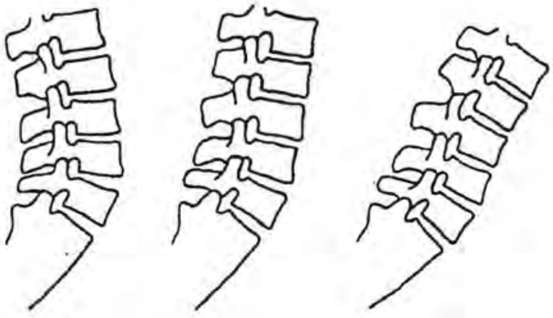
Figure 1 graphically illustrates the predicted orientation of the lumbosacral spine in the torso positions chosen for this analysis. This figure shows the classic lordotic position of the lumbar spine in the neutral posture, and the progressive reduction in lordosis in the flexed postures, as described by several authors (Pearcy et al. 1988). A slight kyphosis is evident at the upper levels of the lumbar spine in the fully flexed posture, also consistent with reports by others (Bogduk 1997). Table 2 presents predicted angles for the superior endplates of S1, L4, and L2 (the inferior vertebrae for the L5-S1, L3-L4, and L1-L2 motion segment, respectively).

3.3 Results of the Analysis of Loads on the Lumbar Spine at 0, 22.5 and 45 degrees of Torso Flexion

Figures 2 - 4 present the results of predicted compression and shear forces on L5-S1, L3-L4, and L1-L2 motion segments of the lumbar spine at 0, 22.5 and 45 degrees of torso flexion. Each figure illustrates the predicted orientation of each of the motion segments, and to the right of each motion segment graphic is a representation of the predicted compression and shear reaction forces acting on the superior endplate of the inferior vertebra of that motion segment.

Table 1. Results of analysis of compression, shear, load rates and resultant forces acting on L5-S1 disk as estimated by the OSU EMG-assisted biomechanical model. Positive A-P shear reaction forces (and negative peak resultant angle values) represent a shear force acting in the anterior direction.

Trunk Flexion Angle (degrees)	n	Averaged Peak Compression Force (N)	Averaged Peak A-P Shear Force (N)	Averaged Peak Resultant Force (N)	Angle of Peak Resultant (degrees)	Averaged Peak Loading Rate (N/s)
0	27	1019.7 (± 252.4)	425.8 (± 98.3)	1106.5 (± 268.9)	-22.7	653.4
22.5	29	2264.5 (± 891.6)	268.5 (± 116.9)	2284.6 (± 888.3)	-6.3	2087.1
45	31	3117.1 (± 1071.8)	-375.2 (± 222.3)	3141.4 (± 1089.3)	6.9	4656.4



0 degrees **22.5 degrees** **45 degrees**

Figure 1. Graphic representation of the predicted orientation of the lumbosacral spine in neutral and forward flexed postures.

Table 2. Superior endplate angles for L2, L4 and S1 vertebrae at three torso flexion angles determined from data and regression equations developed by Chen (2000). Negative values indicate an endplate sloping downward (back to front) with respect to the horizontal. Positive values indicates an endplate sloping upwards (back to front) compared to horizontal.

	Torso Flexion Angle		
	0 degrees	22.5 degrees	45 degrees
L2	10	- 9	-32
L4	-3	- 15	-25
S1	-38	-41	-49

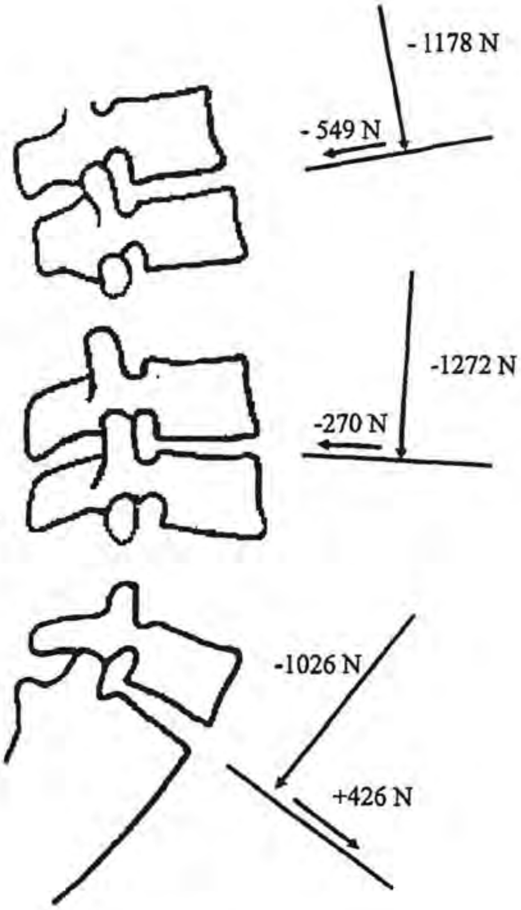


Figure 2. Compression and A-P shear reaction forces acting on the superior endplate of the inferior vertebra of motion segments L1-L2, L3-L4, and L5-S1 with the torso in the neutral posture (0 degrees flexion).

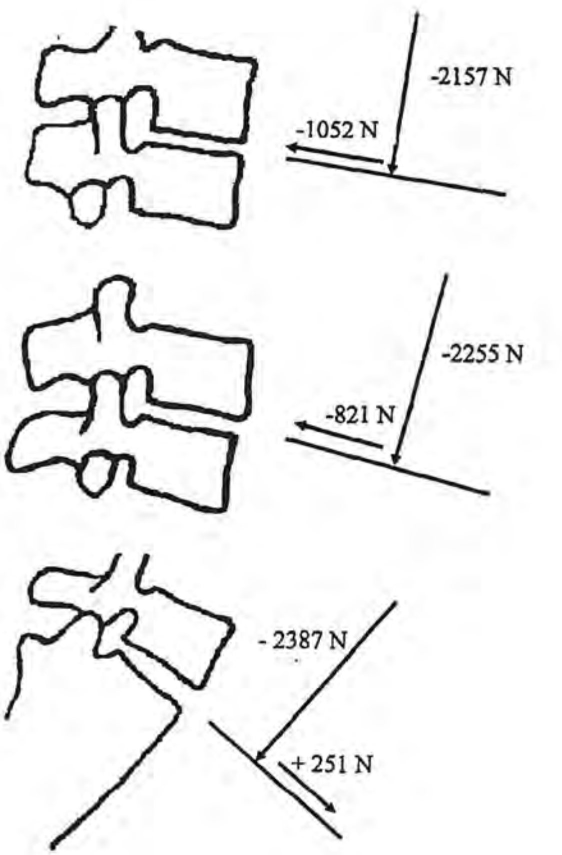


Figure 3. Compression and A-P shear reaction forces acting on the superior endplate of the inferior vertebra of motion segments L1-L2, L3-L4, and L5-S1 with the torso flexed forward 22.5 degrees.

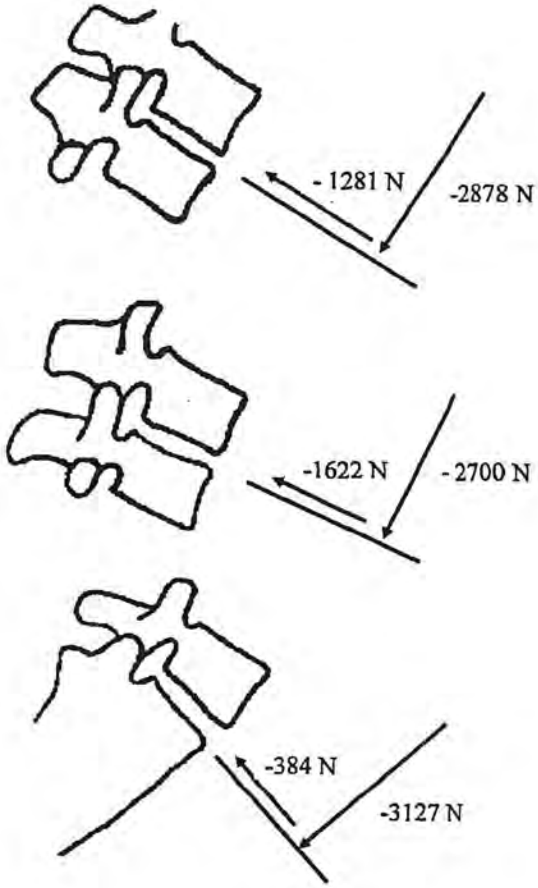


Figure 4. Compression and A-P shear reaction forces acting on the superior endplate of the inferior vertebra of motion segments L1-L2, L3-L4, and L5-S1 with the torso flexed forward 45 degrees.

Compression reaction forces act in a negative direction in the z axis, which is considered perpendicular to the line describing the superior endplate of the inferior vertebra. Negative values for A-P shear indicate a posterior reaction force and vice versa.

4. DISCUSSION

Results of analyses of L5-S1 disc loads in neutral and forward flexed torso postures illustrate the striking influence that torso posture has on the compression and shear forces experienced by the low back at the point of peak force during lifting tasks, as well as the rate at which these forces are applied. Compared to the neutral posture, for example, adopting a 22.5 or 45 degrees torso flexed posture results in a doubling or tripling of the compressive load on the spine, and a seven-fold increase in the load rate. Changes in torso posture also result in changes in the magnitude and direction of the A-P shear forces. Lumbosacral joint shear reaction forces were directed anteriorly in both the neutral posture and partial trunk flexion with less shear evident in partial flexion. In full flexion, however, the shear reaction force was directed posteriorly. The magnitude of the resultant force, dominated by compression, closely followed that of the compressive component; however, the change in magnitude and direction of the A-P shear forces caused the angle at which the peak resultant was operating to swing nearly 30 degrees with respect to the superior endplate of S1 over the range of torso flexion angles studied.

While anterior shear forces were experienced at the lumbosacral joint in neutral and 22.5 degrees of torso flexion, when the resultant was translated to upper levels of the lumbar spine, shear forces acted in a posterior direction no matter the posture. These shear forces were fairly modest at the upper lumbar levels in the neutral posture, but were estimated to be quite substantial in full flexion. Shear values obtained in the most extreme torso flexion condition were greater than 1200 N, and approached shear tolerances for the spine, estimated to be in the range of 1800-2800 N (Krypton et al. 1995). Interestingly, the average shear loads calculated at the lumbosacral disc remained modest no matter which posture was used, being less than 430 N in all cases. It may be possible that the anatomy of the lumbar spine, in particular the lumbosacral junction, with it's significant lordosis, may play an important role in limiting the amount of shear experienced at the lumbosacral joint, resulting in a predominately compression load without much shearing, throughout a wide range of torso flexion.

Results of the regression analysis of data regarding the flexion of motion were consistent with that of other researchers who have examined the flexion of motion segments in trunk flexion (Pearcy et al. 1988, Chen 2000). Results of this analysis suggest that the greatest flexion occurs at the lower and middle levels of the lumbar spine with a lesser contribution at the L1-L2 motion segment. The amount of motion segment flexion observed at 45 degrees of trunk flexion suggests that motion segments at all levels are still capable of several additional degrees of flexion based on results of studies examining full range flexion of the spine (Pearcy et al. 1988, Adams and Hutton 1982).

5. CONCLUSIONS

Based on the analysis of loads acting on the lumbar motion segments in neutral and flexed torso postures, the following conclusions are drawn:

1. The magnitude of the peak resultant force in 22.5 and 45 degrees torso flexion is approximately double and triple that observed in the neutral posture, respectively.
2. Shear forces remained modest at the lumbosacral joint and were directed anteriorly in neutral and 22.5 degrees of torso flexion and were posterior in direction in 45 degrees of torso flexion. Shear forces were estimated to be quite significant at the upper lumbar levels in torso flexion and always acted posteriorly.
3. Estimated load rates were greatly affected by the torso flexion position when lifting. The averaged peak load rates were fairly modest in the neutral posture (650 N/s), but quite high in 45 degrees torso flexion (4650 N/s).

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