

ANALYSIS AND MEASUREMENT OF LUMBAR TRUNK LOADS IN TASKS INVOLVING BENDS AND TWISTS

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Abstract—Ten subjects performed isometric weight-holding and force-resisting work tasks while standing upright, both with and without a twist of the trunk; with the trunk bent laterally; and in postures involving combinations of bending and twisting. The lumbar trunk muscle contraction forces and the lumbar spine compression and shear forces imposed by these tasks were predicted using a biomechanical model. Myoelectric activity was recorded quantitatively at eight locations over the back muscles and at four locations over the abdominal wall muscles. Correlation coefficients from 0.67 to 0.88 were found between the predicted muscle contraction forces and the measured myoelectric activities when the predictions were made so as to minimize muscle contraction force per unit area. Trunk twisting and lateral bending were found to load the spine and trunk muscles less than trunk flexion or holding of weights in front of the body.

INTRODUCTION

In a previous study a mathematical model to determine the loads imposed on the trunk muscles by physical tasks was validated using electromyography (Andersson *et al.*, 1979). The validation was based on laboratory measurements of the myoelectric activities of several trunk muscles when healthy subjects were asked to perform tasks in which their trunks were upright. The model predictions of the muscle tensions were highly correlated to the measured myoelectric activities. In actual life, more complex postures are often assumed; postures involving twisting and lateral bending of the trunk. The aims of the present study were to test the validity of the model in these more complex circumstances, to develop a better understanding of the biomechanics of these activities, and to develop more extensively practical methods to determine the loads imposed on the trunk by work task performance.

MATERIAL AND EXPERIMENTAL METHODS

Subject material

Ten male university students participated. Their ages ranged from 23 to 34, with mean of 28.5 yr; heights ranged from 166 to 194, with a mean of 183 cm; and weights ranged from 65 to 97, with a mean of 75.5 kg. All subjects were in good health and none had a previous history of significant low-back or other health impairment. Clinical examination did not reveal any diseases or abnormalities.

Tasks studied

A total of 20 tasks were studied. All studies were performed with the subjects standing in a reference frame with feet and legs in comfortable positions and with their pelvises strapped to a support board. In the first seven of the tasks a harness was placed around the chest just under the arms. Cords were run horizontally from the harness over sets of pulleys and weights were hung from the cords. The subjects were asked to remain upright and resist the weight applications. In the first of these tasks the subjects were standing relaxed and no weight was applied. In flexion and extension resist tasks, a 15 kg weight was applied, either directly anterior or posterior to the trunk. In two right lateral bending-resist tasks, weights of 10 kg and then 20 kg were applied directly to the right of the subjects. In two twist-resist tasks, two 10 kg weights and then two 20 kg weights were applied to impose pure longitudinal twisting moments. To that purpose, one weight was hung directly in front of the left anterior axillary fold, and one directly behind the right posterior axillary fold.

In the next three tasks, the subjects continued to face forward. In one they extended both arms laterally and held weights of 2 kg in each hand. In the other two, they bent their trunks to the right so that it was inclined 20° laterally as measured by a goniometer placed at the T7 level of the back. They then placed their hands one at each shoulder at first holding no weight, and then holding 4 kg in the right hand.

For the next eight tasks, the subjects twisted to the right so that the line joining their two shoulders made a 45° angle with its original direction in facing forward. The pelvis was held in its original position, and not allowed to rotate. In this configuration the first task was to stand relaxed. A second was to extend both arms laterally while holding 2 kg in each hand. A third was to extend only the left arm, and a fourth to extend

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only the right arm, both while holding 2 kg in the extended hand. In the other four tasks performed with a 45° shoulder twist, both hands were held at the chest and then both hands were extended anteriorly. In each position of the hands, no weight was held at first and then a 2 kg weight was held in each hand.

In the final two tasks, the shoulders were again twisted 45°. The trunk was then flexed 30° at the hips, measured with a goniometer. In one task, the hands were held at the chest; in the second they were extended anteriorly while holding 2 kg weights in each.

MEASUREMENT OF CONFIGURATION DATA

Three targets were taped onto the subject's right side; one transverse to the mass center of the head, one transverse to the mass center of the trunk at approximately the T9 level, and one transverse to the center of the L3 vertebra. Scales were placed on the reference frame in front of and on the right side of the subject. The horizontal scales, two plumb-bobs and the targets were used to estimate both the antero-posterior and the medio-lateral locations of the mass center of the head, the mass center of the trunk, the center of L3, and the center of the right and left hands.

In the horizontal force-resist tasks, the vertical distances from the cord to the L3 level were measured with tape in the flexion-extension, and lateral bend-resist tasks. The horizontal distance between the two cords in the twist-resist task was also measured with a tape. This was done so that the moments of the external forces at the L3 center could be computed. The width and depth of the trunk at the L3 level were also measured in each subject.

MEASUREMENT OF MYOELECTRIC ACTIVITY

Myoelectric signals were picked up by twelve pairs of bipolar, recessed surface electrodes. Six of them were placed on the right and six on the left side of the body so as to have bilateral symmetry in electrode pair locations. The bipolar axis was aligned parallel to the direction of the muscle fibers in each case. Posteriorly, electrode pairs were placed 3 cm lateral of the midline of the spine at the C4, T8 and L3 levels. Another electrode pair was placed 6 cm lateral of the midline at the L3 level. Anteriorly, a pair of electrodes was placed over the rectus abdominis muscle at the level of the umbilicus and 2 cm lateral of the midline. Another pair was placed over the oblique abdominal muscles, 3 cm medial and superior to the anterior iliac spines. A ground electrode was placed on the right ankle.

The myoelectric signals were fed to differential preamplifiers contained in a 0.4 kg box which was strapped to the subject's chest. The signals were further amplified and recorded on magnetic tape. For analysis, the tape signals were first fed to a detector and then to the analog-to-digital converter of a PDP-15 computer. The true RMS detector included a low-pass filter with a 3 dB frequency limit set at 0.8 Hz. The analog-to-

digital conversion rate for the filtered RMS signal was 6 Hz.

Task performance and data evaluation procedures

All tasks were performed quasi-statically. Once steady-state conditions were achieved, the myoelectric recording equipment was started and configuration measurements were made. Recordings were made for 15 s, after which the subject rested for one minute. For each of the 20 tasks, the means over the 10 subjects of the myoelectric signal levels at each electrode location were computed. In addition a calculation was made of the mean of these means over the two L3 electrode pairs on each side (3 cm and 6 cm lateral to the midline).

ANALYSIS OF TRUNK MUSCLE CONTRACTION FORCES AND SPINE COMPRESSION LOADS

The analysis of the trunk internal forces imposed by each task on each subject was carried out in two main steps. The first was to compute the net reaction at the L3 transverse trunk cross-section, and the second to estimate a set of trunk muscle contraction forces and motion segment compression and shear loads acting at L3 that could provide that net reaction.

The net reaction was computed from equilibrium considerations. All external and body segment weight loads and their lines of action were substantially known from the configuration measurements taken. The three mutually perpendicular components of the net reaction force and the corresponding three components of the net reaction moment that must be supplied to equilibrate the trunk segment above that cross-section were determined from the six available equations of equilibrium.

To estimate the muscle and motion segment internal forces, the L3 motion segment was assumed to provide compression and shear resistances, but no significant moment resistance. Intra-abdominal pressure was assumed to be zero. Five bilateral single muscle equivalents were assumed to act across the L3 section (Fig. 1). These represented the rectus abdominis, the internal and external oblique abdominal muscles, the erector spinae muscles, and those parts of the latissimus dorsi muscles which are present in the lumbar region. Linear programming was used to solve for these ten unknown muscle forces so that (1) the three equations of moment equilibrium were satisfied; (2) the muscles experienced only tensile forces; (3) the prescribed value of maximum contraction intensity was not exceeded and (4) an objective function was given minimum value.

Each of the two objective functions was used in turn. One led to the minimization of the compression on the L3 motion segment. When this was used, the maximum contraction intensity was limited to 100 N/cm² in any muscle. The second led to the approximate minimization of the largest muscle contraction intensity. To do this, the maximum allowed contraction

intensity was first set to 5 N/cm². If no solution to the linear programming problem existed at this intensity, the allowed intensity was increased by 5 N/cm² and another solution trial was made. This intensity incrementation process was repeated until a solution was found.

Once the linear programming problem was solved, the remaining equations of force equilibrium were solved for the two motion segment shear forces and for the compression if that had not already been found. By these procedures, estimates of all of the contraction forces in the ten muscle equivalents and the three motion segment resistance forces were calculated. The procedures are described in greater detail by Schultz and Andersson (1981). Trunk cross-sectional geometry was scaled for each subject from his measured trunk diameters in proportions specified in Fig. 1.

Correlation of myoelectric activities and force estimates

The mean over the 10 subjects of each force estimate in each of the 20 tasks was calculated. Linear regression analyses were then made between the force estimate means and the myoelectric signal level means. The myoelectric activity picked up by the rectus abdominis electrodes and the sum of the activities picked up by the lumbar erector spinae electrodes were correlated on each side with the corresponding con-

traction force estimate. The myoelectric activity in the oblique abdominal electrodes was correlated on each side with the sum of the internal and external oblique contraction force estimates. Each regression involved 20 data pairs, one for each task.

RESULTS

Forces imposed on the L3 motion segment

The means over the ten subjects of the compression loads imposed on the L3 motion segment by the 20 tasks ranged from 470 to 2610 N (Table 1). The mean anteroposterior or lateral shear forces imposed on L3 were at most 200 N. The motion-segment loads calculated when the muscle contraction intensity was minimized did not differ much from those calculated when the spine compression was minimized.

Trunk muscle contraction forces

The means over the ten subjects of the calculated muscle contraction forces on one side in the erector spinae muscles ranged to approximately 1100 N, and those in the abdominal obliques to 290 N (Table 2). In the rectus abdominis, the calculated force per side was at most 170 N, and for most of the tasks, it was zero. The choice of the objective function affected the contraction forces calculated, but only moderately. Clear distinctions could be made between those exercises which were more and those which were less strenuous, regardless of which of the two objective functions was used. In the minimum intensity solutions, the largest required mean muscle contraction intensity was 44 N/cm² (440 kPa).

Most of the activities studied imposed only small loads on the spine and called for only small muscle contraction forces. The exercises involving twisted or laterally bent body configurations did not load the trunk structures significantly more than sagittally-symmetric configured exercises involving comparable external loads. The largest spine loads, and generally the largest muscle contraction forces, were imposed by the two exercises involving 30° of trunk flexion. There, even when the hands were placed close to the chest and no weights were held, the loads imposed well exceeded those imposed by any of the other 18 exercises.

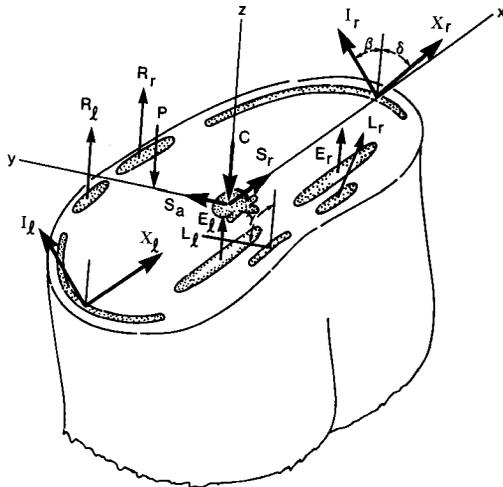


Fig. 1. Schematic of the model used for internal force estimation. The five bilateral pairs of single muscle equivalents represent the rectus abdominis, the internal and external oblique abdominal, the erector spinae, and those parts of the latissimus dorsi muscles which cut the trunk sectioning plane. Contraction forces in these model muscles are denoted R, I, \bar{X} , E and L respectively, with the subscripts denoting left and right sides. Inclination angles, β , δ and γ were all set to 45°. Motion segment compression force is denoted C, anterior shear force S_a and right lateral shear force S_r . Abdominal cavity pressure resultant P here was set to zero. Muscle cross-sectional area per side were taken as, respectively for R, I, \bar{X} , E and L; 0.006, 0.0168, 0.0148, 0.0389 and 0.0037 times the product of trunk cross section depth and width. Centroidal offsets in the anteroposterior direction were, in the same order, taken as 0.54, 0.19, 0.19, 0.22 and 0.28 times trunk depth. In the lateral direction, they were taken as 0.12, 0.45, 0.45, 0.18 and 0.21 times trunk width.

Correlations between predicted muscle forces and measured myoelectric activities

The mean calculated muscle contraction forces and the mean measured myoelectric activities were in general well-correlated (Table 3, Figs 2-4). With the minimum contraction intensity assumption, the linear correlation ranged from 0.67 to 0.88 over the six muscle force/activity correlations made. The coefficients were more variable when the minimum compression assumption was used, ranging from 0.34 to 0.92. The poorest force-activity correlations were obtained for the abdominal oblique muscles when the minimum compression objective function was used to predict the muscle tensions.

Table 1. Mean predicted forces (N) on the L3 motion segment using the two different objective functions

| Task performed | Minimum compression solution | | | Minimum intensity solution | | |
|--|------------------------------|------------|----------|----------------------------|------------|----------|
| | Compr. | Latl shear | AP shear | Compr. | Latl shear | AP shear |
| <i>Standing without twist</i> | | | | | | |
| Stand relaxed | 470 | 0 | 0 | 500 | 0 | 0 |
| Resist flex, 15 kg* | 1390 | 0 | 150 | 1460 | 0 | 150 |
| extn, 15 kg | 690 | 0 | -150 | 970 | 0 | -170 |
| latl bend, 10 kg | 620 | 90 | 40 | 670 | 60 | 30 |
| latl bend, 20 kg | 880 | 150 | 50 | 1150 | 110 | -10 |
| twist, 10 kg | 730 | 150 | 100 | 860 | 30 | 40 |
| twist, 20 kg | 970 | 160 | 130 | 1100 | 50 | -50 |
| Bend right, hold 4 kg | 840 | 110 | 40 | 940 | 10 | 0 |
| Arms latl, hold 2 + 2 kg | 500 | 0 | 0 | 520 | 0 | 0 |
| <i>Standing with 45° twist</i> | | | | | | |
| Stand relaxed | 480 | 0 | 0 | 500 | 0 | 10 |
| Arms latl, hold 2 + 2 kg | 640 | 0 | 0 | 680 | 0 | 0 |
| Hands at chest, 2 + 2 kg | 780 | 20 | 10 | 810 | 0 | 0 |
| Arms anterior, 2 + 2 kg | 1190 | 40 | 20 | 1380 | 10 | 0 |
| <i>Standing twisted and flexed 30°</i> | | | | | | |
| Hands at chest | 1700 | 0 | 180 | 1800 | 0 | 180 |
| Arms anterior, 2 + 2 kg | 2290 | 0 | 200 | 2610 | 0 | 200 |

*The mean moments imposed on L3 by these weights in the six resist tasks were 44.3, 40.3, 27.6, 55.8, 25.6 and 51.2 N m.

Tabulations of the results obtained that provide more detail than that practical to give here are available from the authors upon request.

DISCUSSION

In our earlier studies of the performance of simple physical tasks, we found that our model-based predictions of trunk internal forces uniformly correlated well with our experimental measurements (Andersson, *et al.*, 1979; Schultz and Andersson, 1981; Schultz, *et*

al., 1982a; Schultz, *et al.*, 1982b). In the present study, the regression coefficients are less impressive. But, the weaknesses in the correlations are not qualitative; there are no major discrepancies in the force/activity relationships. When the model predicted that a muscle should be contracting strongly, that muscle consistently showed a comparatively large myoelectric activity. When the predicted contraction was small, the myoelectric activity was consistently small. The model seems to be valid in at least a semi-quantitative sense, even for the complex maneuvers studied here.

Two sources of quantitative shortcomings in the

Table 2. Mean trunk muscle contraction forces (N) required for some of the tasks. These were calculated using the minimum intensity solutions. Rectus abdominis and latissimus dorsi contraction forces were at most 90 and 110 N. E = erector spinae, I = internal abdominal oblique, \bar{X} = external abdominal oblique. Subscripts indicate left or right side

| Task performed | E _L | E _R | I _L | I _R | \bar{X} _L | \bar{X} _R | Required intensity (N/cm ²) |
|-------------------------------------|----------------|----------------|----------------|----------------|------------------------|------------------------|---|
| <i>Standing without twist</i> | | | | | | | |
| Stand relaxed | 60 | 60 | 0 | 0 | 0 | 0 | 6 |
| Resist flex, 15 kg | 510 | 510 | 0 | 0 | 0 | 0 | 23 |
| extn, 15 kg | 0 | 0 | 160 | 160 | 140 | 140 | 23 |
| right bend 10 kg | 110 | 40 | 60 | 20 | 70 | 20 | 14 |
| right bend 20 kg | 310 | 120 | 50 | 50 | 120 | 40 | 23 |
| twist, 10 kg | 60 | 210 | 170 | 0 | 0 | 110 | 19 |
| twist, 20 kg | 80 | 260 | 290 | 0 | 0 | 220 | 31 |
| Bend right, hold 4 kg | 340 | 30 | 10 | 10 | 90 | 0 | 15 |
| Arms latl, hold 2 + 2 kg | 50 | 50 | 0 | 0 | 0 | 0 | 6 |
| <i>Standing with 45° twist</i> | | | | | | | |
| Stand relaxed | 50 | 50 | 0 | 0 | 10 | 10 | 7 |
| Arms latl, hold 2 + 2 kg | 100 | 150 | 0 | 10 | 0 | 10 | 9 |
| Hands at chest, 2 + 2 kg | 250 | 140 | 10 | 0 | 10 | 0 | 11 |
| Arms anterior, 2 + 2 kg | 580 | 210 | 90 | 0 | 90 | 0 | 24 |
| <i>Stand twisted and flexed 30°</i> | | | | | | | |
| Hands at chest | 700 | 670 | 10 | 0 | 10 | 0 | 30 |
| Arms ant., 2 + 2 kg | 1120 | 860 | 110 | 0 | 110 | 0 | 44 |

Table 3. Correlation coefficients between mean calculated muscle contraction forces and mean measured myoelectric activities

| Muscle | Function used to predict muscle forces | |
|---|--|-------------------------------|
| | Minimum spine compression | Minimum contraction intensity |
| Erector spinae | | |
| Left side | 0.86 | 0.88 |
| Right side | 0.60 | 0.74 |
| Rectus abdominis | | |
| Left side | 0.82 | 0.70 |
| Right side | 0.92 | 0.83 |
| Sum of internal and external abdominal oblique forces | | |
| Left side | 0.55 | 0.77 |
| Right side | 0.34 | 0.67 |

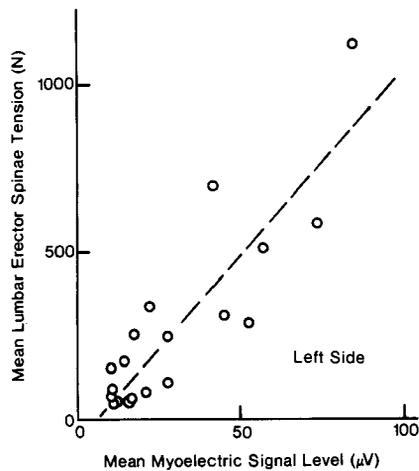


Fig. 2. Predicted contraction forces vs measured myoelectric activities in back muscles on the left side. Each point shows ten-subject mean values of forces and of electrical activities for one task. The regression line for the data pairs is shown. Data for tasks calling for zero muscle tensions are not shown, but were included in the linear regression analysis. The forces shown are those predicted using the minimum contraction intensity assumption.

correlations need to be considered; the surface myoelectric activities might not relate to the contraction forces in specific muscles accurately enough, and/or the force predictions might lack quantitative precision. The former source is particularly troublesome in the oblique abdominal muscles, because the results show clearly that those electrodes picked up the activity in both the external and internal abdominal oblique muscles. Since we do not yet know fully how to interpret those signals, we arbitrarily correlated them with the sum of the contraction forces in the two muscles. More research is needed to learn how to better interpret those signals. Activity measurements utilizing electrodes implanted into each of those two muscles might contribute to that goal.

The accuracy of the force predictions depends on the

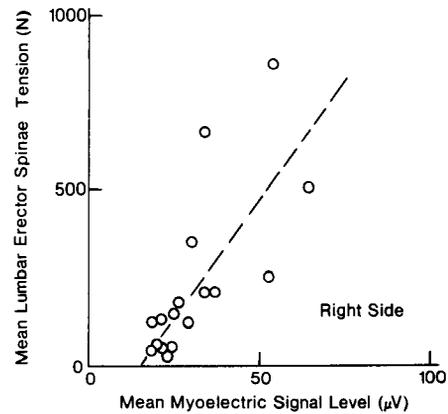


Fig. 3. Predicted contraction forces vs measured myoelectric activities in back muscles on the right side. See Fig. 2 caption for explanation.

task being analyzed. Predictions of contraction forces in tasks involving extension, lateral bending and twisting moments are more questionable than those involving flexion moments. Tasks involving flexion moments call primarily on the erector spinae muscles; tasks involving extension, lateral bending and twisting moments tend to recruit many of the lumbar trunk muscles. The fibers of the erector spinae all lie close to the centroid of the muscle cross-sectional area, so that these muscles have homogeneous and easily defined lines of action. The fibers of the latissimus dorsi and the two abdominal oblique muscles are spread out. These muscles have more variable and less easily defined lines of action. The erector spinae with their almost purely longitudinal lines of action have relatively simple mechanical actions, while the latissimus dorsi and the oblique abdominal muscles with their curved and inclined lines of action have more diverse actions. So that is easier to represent accurately the erector spinae muscles in a model by single muscle equivalents than it is to represent the latissimus dorsi or the oblique abdominal muscles.

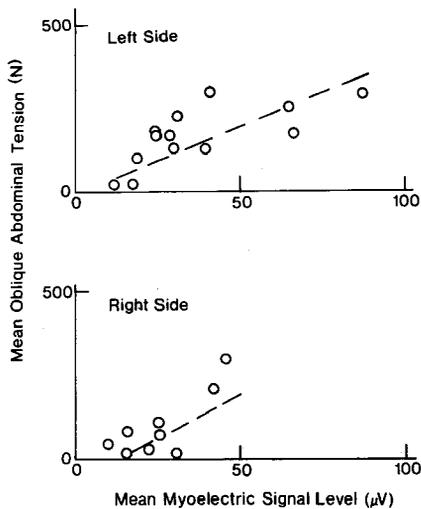


Fig. 4. Predicted contraction forces vs measured myoelectric activities in the abdominal oblique muscles. See Fig. 2 caption for explanation. The tensions indicated are the algebraic sums of the predicted contraction forces in the internal and external abdominal oblique muscles.

Moreover, little is known about how muscles are recruited when several options of the accomplishment of a task are available. Muscle recruitment patterns under those circumstances probably are not unique; they can vary from person to person and from time to time in any one person. Tasks involving primarily flexion moments are not of this kind. The erector spinae are the major contributors to resisting trunk flexion, so essentially only one option is available for most flexion resistance tasks. Several options are available to provide each of extension, lateral bending and twist resistances, recruiting different combinations of the rectus abdominus, the oblique abdominals, the erector spinae and the latissimus dorsi. For these reasons, the adequacy of the muscle representation and the choice of the objective function are seldom critical in the analysis of tasks that involve primarily flexion moments; they are much more critical in the analysis of tasks that involve extension, lateral bending and twisting moments. Our earlier studies considered primarily tasks of the former kind; the present study considers a number of tasks of the latter kind.

During the most strenuous of the performances studied some subjects showed or expressed slight fatigue. However, every subject was able to perform every task for the 15 s period required and the next task was begun only after the subject said he was rested. There were no indications that fatigue affected myoelectric signal quality. Intra-abdominal cavity pressure was assumed to be zero in biomechanical analyses based on our previous experience. Schultz *et al.* (1982b) found that in 15 s quasi-static performances of tasks similar to those studied here, intra-abdominal pressures were rather small (1–6 kPa) and provided a relief of spine compression averaging only 14%. Since in these present experiments we did not measure intra-

abdominal pressure, it seemed reasonable to make this assumption about it.

Similarly, in earlier work we examined the use of myoelectric activity data normalized to the maximum electric activity recorded by that electrode for that subject. This normalization procedure did not significantly reduce the interindividual variation. For this reason we used myoelectric activity data in absolute form for this study. Myoelectric activity in the lumbar portions of the latissimus dorsi was not recorded, so it is not known how good our model was in predicting their contraction forces.

It is sometimes said that performances of tasks involving trunk twisting or lateral bending, or combinations of these with anterior bending, unduly load the lumbar trunk structures. Neither the model analyses nor the myoelectric measurements indicate that this is the case. Whenever two similar tasks were performed, one with and one without a trunk twist, the predicted loads or the measured myoelectric activities were found to differ only slightly. Our results suggest that twisting does not have much effect on trunk loads in the situations we studied.

The need to support weights placed well anterior to the spine, as when weights are held by anteriorly outstretched hands or when the trunk is flexed so that upper body segment mass centers move out anteriorly, loads the spine structures and trunk muscles heavily. This occurs because the flexion moments these weights produce must be balanced by contractions of the posterior back muscles. Since these muscles act on the spine through short moment arms, they must contract strongly to achieve the desired moment balance. But whether or not such tasks involve a trunk twist seems to make little difference. It is the flexion moment rather than the twist that is responsible for the large loads. For example, in the present experiments, holding 4 kg in the anterior outstretched hands with the trunk flexed 30° and twisted 45° imposed an L3 compression force of at least 2290 N and required total posterior back muscle longitudinal contraction forces of at least 1950 N. Schultz, *et al.* (1982a) reported that a similar activity, when performed without the trunk twist, imposed an L3 compression of 2220 N and required a muscle contraction force of approximately 1870 N. The corresponding figures for holding 4 kg in the nearly outstretched arms while standing upright without a twist were 960 N and 550 N while the same task performed with fully outstretched arms and with a 45 degree trunk twist called for forces of 1190 N and 750 N. In determining the loads imposed on the spine, trunk forward bending is important while trunk twisting seems to matter little.

Similarly, none of the studied activities involving a lateral bend of the trunk or the lateral holding of weights loaded the spine or the trunk muscles heavily. The imposition of lateral bending moments can load the spine moderately, but not nearly as much as the imposition of flexion moments can. This occurs because the trunk cannot be laterally offset very much,

so that the moment imposed by the laterally offset trunk weight cannot become very large. In addition, the lateral abdominal wall muscles act on the spine through a relatively large moment arm, so they need not contract strongly to counterbalance the offset weight moment.

CONCLUSIONS

The biomechanical model used in these studies to calculate the loads imposed on the lumbar trunk structures during performance of tasks involving trunk bending and twisting predicts those loads moderately well, but not as well as it can predict the loads imposed by sagittally symmetric tasks that tend only to flex the trunk.

Further research is needed to examine patterns used for the recruitment of the trunk muscles when different options are available for that recruitment. Trunk muscle myoelectric activities need to be measured with intramuscular electrodes, to delineate more carefully what muscles contract, to what degree, and to what extent the different parts of a muscle can contract independently of each other.

Trunk twisting by itself does not seem to load the spine or trunk muscles very much. Trunk flexion and other activities that impose large flexion moments load these trunk structures heavily, whether or not accompanied by twisting.

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