Analysis of Loads on the Lumbar Spine

ALBERT B. SCHULTZ* and GUNNAR B. J. ANDERSSON†

This paper presents procedures to calculate the loads on the lumbar spine and the contraction forces in the trunk muscles that are likely to be produced by given physical activities. [Key Words: low-back pain, spinal loading, internal forces]

LOADS ON THE LUMBAR spine should be kept as light as possible for several reasons: preexisting lumbar spine conditions can be aggravated by heavy loads; workers with back pain lose more days from work when their jobs involve heavy loads; and it is suspected that heavy loads have a role in causing back pain. If heavy loads are to be avoided, it is necessary to know under what circumstances they arise. While this can be learned from epidemiological studies or through laboratory and work place experiments involving different measurement techniques, it is safer, easier, faster, and less expensive to determine the loads on the lumbar spine by biomechanical analysis. The purpose of this paper is to explain ways in which the loads on the lumbar spine that result from any physical activity can be calculated. The calculation schemes described can be used to determine the loads on any part of the body, human or otherwise, but the schemes will be applied here only to determine loads on the human lumbar spine.

This paper is concerned mainly with quasi-static or, equivalently, quasi-isometric physical activities. Many physical activities can be analyzed as if they were executed statically, even when they involve movement. In some activities, however, body dynamics must be taken into account. A discussion of when this is the case and how dynamics can be accounted for will be reserved for the end of the paper, since the same general calculation procedures are employed in either situation.

People are quite variable, both in their anthropometric characteristics and in the specific way they execute an activity, and the activities they perform are quite diverse. The compression load on the lumbar spine, for example, might be near zero in quiet lying, 400 Newtons (N) in quiet standing, and 4,000 N in a strenuous exertion. Because the range of loads experienced is so large, even a rough estimate of the loads generated by an activity will usually suffice for the solution of practical problems.

SOME GENERAL ASPECTS OF THE PROBLEM

To compute the loads on the lumbar spine created by a physical activity, the body is first visualized as being divided into upper and lower parts by an imaginary transverse cutting plane. The cutting plane is passed through the level of the lumbar spine at which the loads are to be determined. Newton's Laws are then applied to the upper part, and a two-stage calculation procedure is carried out. In the first stage, the net reaction is computed; in the second, the internal forces are estimated.

From the Department of Materials Engineering, University of Illinois at Chicago Circle,* Chicago, Illinois, and the Department of Orthopaedic Surgery I, Sahlgren Hospital,† Gothenburg, Sweden.
Presented at the Sixth Annual Meeting of the International Society for the Study of the Lumbar Spine, Göteborg, Sweden, June 1, 1979.
Supported by U.S. Public Health Service Grants OH 00514 and AM 15575, Development Award AM 00029, and the Swedish Work Environment Fund.
Submitted for publication May 5, 1980.
The assistance of Karol Haderspeck is gratefully acknowledged.
0362-2436/81/0129-0076$0100

COMPUTATION OF THE NET REACTION

The net reaction consists of six components: three net force components and three net moment components. These forces and moments must be supplied by the part of the body below the imaginary cutting plane to act on the part of the body above the plane, in order to keep the upper body in equilibrium. The net force is equivalent to the vector sum of all the internal forces acting across the cutting plane, and the net moment is equivalent to the vector sum of the moments of all those forces taken about some arbitrary point. Since in the circumstances under consideration the upper part of the body must be in equilibrium, there is little question about the nature of the net reaction. It is determined from the six requirements for equilibrium that result from Newton's Laws; the sums of all the net reaction and external forces acting on the upper body in each of the x, y, and z directions and the sums of all their moments about each of the x, y, and z axes must be zero. These requirements provide six equations that are solved to find the six components of the net reaction.

To calculate the net reaction, a coordinate system is first established. We place its origin at the center of the vertebral body cut by the imaginary plane and assume that the net reaction acts at that point. Coordinate directions are selected as follows: the x axis is positive to the right, the y axis positive anteriorly, and the z axis positive superiorly. The x and y axes lie in the transverse cutting plane, with their orientations referred to the orientation of the vertebral body; the z axis is perpendicular to the cutting plane (Figure 1).

The next step is to consider the external loads acting on the upper body. These are of two types: loads applied in order to execute the task and loads from body segment weights. The applied loads are the forces needed to maneuver (lift, push, etc.) any object being handled; they are usually applied to the hands and can be measured directly. The weight loads act at the centers of mass of the upper body segments. The weights of different body segments can be found in the literature (Clauser et al,[3] for example). Mass-center locations can be estimated using scaled cross-sectional anatomical drawings (Eycleshymer and Schoemaker,[5] for example) and assuming that the body parts have uniform densities.

The net reaction is not affected directly by anything occurring in the parts of the body below the cutting plane, nor is it affected by the material properties of the hard and soft tissues of the body. Anatomical variables affect the net reaction only in so far as they influence mass distributions and moment arms. The major difficulty in the determination of a net reaction is to gather the needed configuration data. The process of gathering precise three-dimensional coordinate data for many points can be tedious; approximate data will frequently suffice; z-coordinate data are not needed for loads that act vertically, nor are x-coordinate data needed to analyze sagitally symmetric activities.

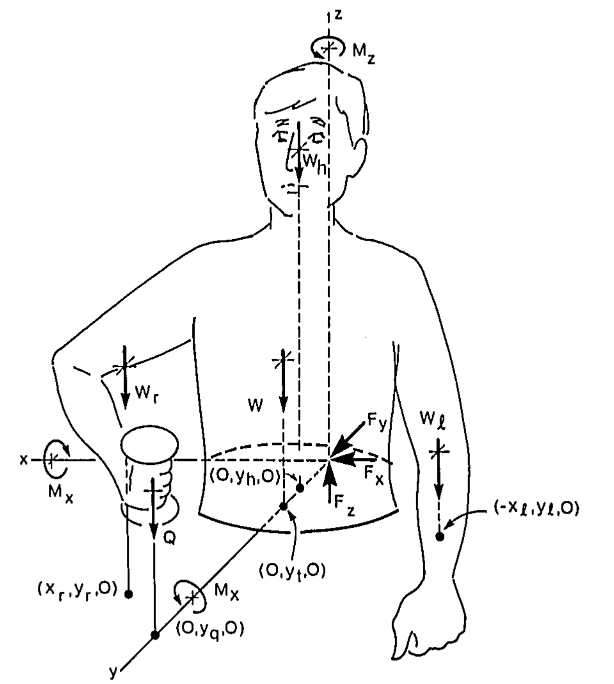


Fig 1. Holding a weight in the right hand: external forces and net reaction components.

Solution of a Sample Problem. These ideas are illustrated by calculation of the net reaction needed to hold a weight of value Q in the right arm (Figure 1). Suppose that the weight of the upper body is divided into the weight of the head and upper neck, W_h; the weights of the left and right upper limbs, W_l and W_r; and the weight of the remainder of the trunk above the cutting plane, W_t.

Based upon body segment weight data, assume that W_t is 36% of total body weight when the cutting plane is passed through the L3 level, W_h is 5% of body weight, and W_l and W_r are each 4.5% of body weight. Place W_t in the middle of the trunk cross section at the T9 level, W_h in the middle of a line joining the centers of the left and right ears, and each limb weight at its mass center's location, which can be estimated by visual observation of limb configuration. We specify the coordinates of the mass center locations as (x_t, y_t, z_t), etc. For reasons already stated, the segment weight and mass center location data need not be known with a high degree of accuracy.

The net reaction consists of the forces and moments F_x, F_y, F_z, M_x, M_y, M_z (Figure 1). It can be computed from the six requirements for equilibrium of the upper body:

Equilibrium of forces in the
x direction: $F_x = 0$
y direction: $F_y = 0$
z direction: $F_z = Q + W_h + W_l + W_r + W_t$

Equilibrium of moments about the
x-axis: $M_x = y_q Q + y_h W_h + y_l W_l + y_r W_r + y_t W_t$
y-axis: $M_y = x_r W_r - x_l W_l$
z-axis: $M_z = 0$

In this simple example, there are no forces in the x or y directions, and no force has a moment about the z-axis. In addition, none of W_h, W_q or W_t has a moment about the y-axis. However, it is a straightforward task to generalize the net-reaction computation scheme illustrated here to more complicated situations.

If the numerical values are assumed as

$Q = 40$ N	$x_q = 0$	$y_q = 45$ cm
$W_h = 35$ N	$x_h = 0$	$y_h = 8$ cm
$W_l = 32$ N	$x_l = 20$ cm	$y_l = 1$ cm
$W_r = 32$ N	$x_r = 15$ cm	$y_r = 24$ cm
$W_t = 252$ N	$x_t = 0$	$y_t = 1$ cm

the three nonzero components of the net reaction are

$$F_z = 391 \text{ N} \quad M_x = 31.3 \text{ Nm} \quad M_y = 1.6 \text{ Nm}$$

The computation of the net reactions needed for equilibrium in some other situations will be described in the next section of this paper.

INTERNAL FORCES THAT CAN PROVIDE THE NET REACTION

The net reaction needed to equilibrate the upper part of the body is supplied in the lumbar trunk by muscle contractions, connective tissue tensions, intra-abdominal pressure, and the resistances supplied by the spine motion segments. These are forces internal to the trunk. The problem is to determine the motion segment resistances or, in other words, the loads on the spine. But in the course of estimating these loads, the other internal forces will need to be estimated as well.

We assume that the lumbar motion segments do not supply significant resistance moments in ordinary activities. A five Nm moment causes a lumbar motion segment to rotate from approximately one to five degrees in bending or torsion (Schultz et al[10]). In physical activities, net reaction moments of 100 Nm or more are frequently developed, while the motion segments each rotate a few degrees at most. So, this is a reasonable assumption. On the other hand, lumbar motion segments can resist significant shear and compression forces with only small linear motions (Berkson et al[2]).

Example 1: A Sagitally Symmetric Problem. To begin showing how internal forces can be estimated, consider a subject holding weights of magnitude Q in his hands in a sagittally symmetric configuration (Figure 2a). The first step is to compute the net reaction. In this problem, four equations of equilibrium are trivially satisfied, since there are no x-direction or y-direction forces and no moments about either the y-axis or the z-axis. The two nontrivially satisfied equations of equilibrium are

$$F_z = Q + W_a + W_h + W_t$$
$$M_x = y_q Q + y_a W_a + y_h W_h + y_t W_t$$

where F_z and M_x are the two nonzero components of the net reaction and W_a is the weight of the two limbs. Assume the following data

$$Q = 40\text{ N} \qquad y_q = 40\text{ cm}$$
$$W_a = 63\text{ N} \qquad y_a = 20\text{ cm}$$
$$W_h = 35\text{ N} \qquad y_h = 6\text{ cm}$$
$$W_t = 252\text{ N} \qquad y_t = 1\text{ cm}$$

The net reaction, from the two equations, is

$$F_z = 390\text{ N}$$
$$M_x = 33.2\text{ Nm}$$

To estimate the internal forces, suppose we first assume that there are only two internal forces that supply this net reaction: a compressive force C on the lumbar motion segment and a tension E in a single equivalent of the erector muscles (Figure 2b). These are the assumptions used by Morris et al.[6] The two forces E and C must provide the net reaction, which consists of F_z and M_x.

So

$$F_z = C - E$$
$$M_x = eE$$

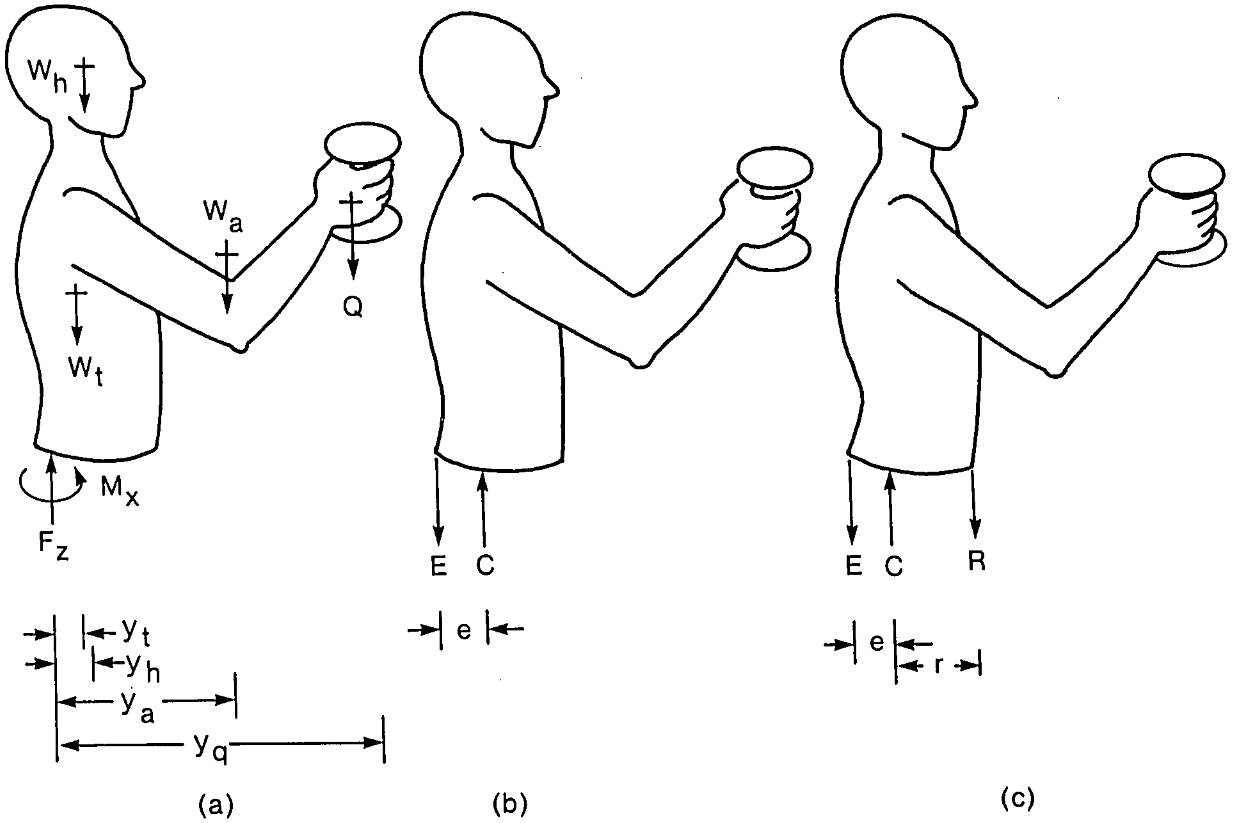


Fig. 2. Data for analysis of a sagittally symmetric weight-holding task.

Take e = 5 cm, and solve these equations to obtain

$$E = \frac{3320\ \text{Ncm}}{5\ \text{cm}} = 664\ \text{N}$$

$$C = 390\ \text{N} + 664\ \text{N} = 1054\ \text{N}$$

The required net reaction can be supplied by these two forces. The value of the internal force C is considerably larger than the value of the net reaction component F_z. Some thought will show that in this example it is mainly the magnitude of the moments of the external forces that cause C to be as large as it is, rather than the magnitudes of the external forces themselves. In general, the magnitudes of the external moments will be found to be the major determinants of the internal force magnitudes. In other words, to keep the loads on the lumbar spine light, keep the moments of the external forces small.

Now consider another possibility, that the rectus abdominus muscle also contracts with tension R when the weight is held (Figure 2c). The net reaction must now be supplied by E, C, and R, and we have

$$F_z = C - E - R$$
$$M_x = eE - rR$$

These two equations involve three unknown forces, so the unknown forces cannot be found from the available equations of equilibrium. Problems of this kind are called statically indeterminate, while problems of the former kind are called statically determinate. In order to solve statically indeterminate problems, additional assumptions must be made. Suppose for illustration that we make the completely arbitrary assumption that R = 200 N. The above two equations can then be solved to obtain, when r = 10 cm,

$$E = 1064\ \text{N} \qquad C = 1654\ \text{N}.$$

The effect of the assumed 200 N rectus contraction is to increase the erector tension by 400 N and the compression on the spine by 600 N.

A General Model for Internal Force Estimation. Now consider the more complicated model of the trunk shown in Figure 3. This model can be used to estimate trunk internal forces in a wide variety of circumstances. It incorporates ten muscle equivalents to represent most of the major muscle groups spanning the lumbar region. The five on the right side are the right latissimus dorsi equivalent, L_r, assumed to act at $(x_1, -y_1)$, at an angle with the z-axis of γ; the right erector equivalent E_r at $(x_e, -y_e)$; the right external oblique X_r at (x_o, y_o), at an angle with the z-axis of δ; the right internal oblique I_r, also at (x_o, y_o), at angle β; and the right rectus abdominus R_r, at (x_r, y_r). There are five corresponding muscle equivalents symmetrically placed on the left side. An intra-abdominal pressure force P is assumed to act at $(0, y_p)$. The spine motion-segment resistances consist of a compression C, a right-lateral shear S_r, and an anterior shear S_a. The three motion-segment resistances are assumed to act at the coordinate system origin.

The requirement that these 14 internal forces provide the six components of the net reaction that are needed

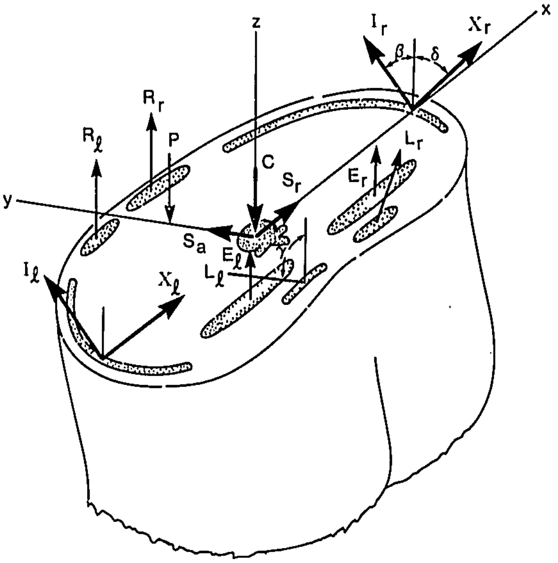


Fig. 3. A general model for internal force estimation.

for equilibrium is expressed by the six equations presented in Table 1. The intra-abdominal pressure resultant can be determined from experimental measurements. The other 13 internal forces are unknown, and only six equations are available to find them, so use of this model leads to a statically indeterminate problem. The next two examples will show two different ways to solve this problem.

Example 2: Nonsymmetric Weight-Holding; Direct Solution. One way to solve the problem of indeterminancy is to make some assumptions about the internal forces, enough of them to render the problem statically determinate. To illustrate this approach, consider once more the situation of Figure 1. The problem is to find the internal forces needed to hold the weight; the required net reaction has already been computed. A reasonable set of assumptions is

$$I_l = 0 \quad L_l = 0 \quad P = 0 \quad R_l = 0 \quad X_l = 0$$
$$I_r = 0 \quad L_r = 0 \quad \quad R_r = 0 \quad X_r = 0$$

In words, these assumptions are that no significant intra-abdominal pressure is used for this activity, that any activity in the latissimus muscles can be included in the erector equivalent muscles, and that antagonistic muscle contractions are minimal. A set of weight data has already been given. The following trunk cross-sec-

Table 1. The Six Equations of Equilibrium Governing the Model of Figure 3.

$$F_x = (L_1 - L_r)\sin\gamma + S_r$$
$$F_y = (I_1 + I_r)\sin\beta - (X_1 + X_r)\sin\delta + S_a$$
$$F_z = C + P - (E_1 + E_r) - (R_1 + R_r) - (I_1 + I_r)\cos\beta - (L_1 + L_r)\cos\gamma - (X_1 + X_r)\cos\delta$$
$$M_x = y_e(E_1 + E_r) - y_r(R_1 + R_r) + y_p{}^P + y_1(L_1 + L_r)\cos\gamma - y_o\{(I_1 + I_r)\cos\beta + (X_1 + X_r)\cos\delta\}$$
$$M_y = x_e(E_r - E_1) + x_r(R_r - R_1) + x_1(L_r - L_1)\cos\gamma + x_o\{(I_r - I_1)\cos\beta + (X_r - X_1)\cos\delta\}$$
$$M_z = y_1(L_r - L_1)\sin\gamma + x_o\{(I_r - I_1)\sin\beta - (X_r - X_1)\sin\delta\}$$

tional geometrical data are representative of a person who has a trunk width of 30 cm and a trunk depth of 20 cm at the L3 level:

$$x_r = 3.6\text{ cm} \quad y_r = 10.8\text{ cm} \quad \beta = 45°$$
$$y_p = 4.8\text{ cm} \quad \delta = 45°$$
$$x_o = 13.5\text{ cm} \quad y_o = 3.8\text{ cm} \quad \gamma = 45°$$
$$x_e = 5.4\text{ cm} \quad y_e = 4.4\text{ cm}$$
$$x_l = 6.3\text{ cm} \quad y_l = 5.6\text{ cm}$$

When the net reaction components and all of the given data are entered into the five Table 1 equations which are not trivially satisfied, the five unknown internal forces are found to be

$$C = 1102\text{ N} \quad E_l = 341\text{ N} \quad S_a = 0$$
$$E_r = 370\text{ N} \quad S_r = 0$$

So, there are two muscle contraction forces, and they are divided between the erectors so as to provide both the extension moment and the lateral bending moment needed for equilibrium.

Example 3: Nonsymmetric Weight-holding; Solution by Linear Programming. Another way to solve this statically indeterminate problem is through use of optimization techniques, as proposed, for example, by Seireg and Arvikar.[13] Linear programming (Dantzig,[4] for example) is probably the simplest of these techniques. We have found it effective particularly for problems involving lateral bending or twisting moments where it is not obvious what assumptions about muscle contractions might be reasonable.

The major question that arises when linear programming or similar procedures are used for solution is the choice of the "objective function" or the quantity to be optimized. Suppose, for illustration, that we choose to minimize the compression on the lumbar vertebra and use the equation for z-direction force equilibrium to do so. The equations for x and y force equilibrium are used to find S_r and S_a after the solution is obtained. The three equations of moment equilibrium, the ten requirements that the muscle tensions not be negative, and the ten requirements that the muscle contraction intensities not exceed a reasonable level (100 N/cm^2) are used as constraints. When this is done, the solution of the same problem is

$$C = 1{,}010\text{ N} \quad E_l = 125\text{ N} \quad L_l = 240\text{ N}$$
$$E_r = 155\text{ N} \quad L_r = 240\text{ N}$$

and other model internal forces have zero values.

This solution differs slightly from the previous solution to this problem. The reason is that some slips of the latissimus dorsi are now included in the model. Since these have somewhat larger extension moment arms than the erector spinae muscles, they do not impose as much compression on the spine per Nm of the extension moment they develop. The solution routine therefore automatically selects them, and in this solution they contract with their maximum allowed intensity. The erectors provide the remainder of the extension moment and all of the lateral bending moment needed for equilibrium. If the latissimus dorsi are removed from consideration, the linear programming routine produces the same solution as that presented earlier. But the human reasoning leading to the assumptions used for the elementary solution is replaced by the logic of a computer program instructed to produce the required net reaction while minimizing the compression on the spine. There must be analogs of such programs in the central nervous system, as people do not usually make conscious decisions as to what muscles should be contracted to execute a physical activity.

Example 4: Resisting a Push to the Left. For another example, consider the calculation of internal forces when a 200 N force pushing to the left is applied to the chest 10 cm superior to L3. The net reaction in this case, if body segment weights are ignored, consists only of a 200 N x-direction force and a 20 Nm bending moment about the y-axis. If the geometrical data and the linear programming procedure just outlined are used to solve for the internal forces minimizing spine compression, the solution obtained is

$$C = 189\text{ N} \quad S_r = 76\text{ N} \quad I_r = 57\text{ N}$$
$$S_a = -32\text{ N} \quad L_r = 108\text{ N}$$
$$X_r = 102\text{ N}$$

and other model internal forces have zero values.

In this solution, all the muscles on the left side are silent since the objective function demands minimal antagonistic activity. The rectus abdominus and the erector muscles on the right side are silent because the arms through which they can develop a right lateral bending moment are relatively small. The objective function discriminates against unnecessary use of such muscles. The two oblique muscles and the latissimus dorsi on the right side are utilized. The reason all three are used is that three requirements need to be satisfied; the net lateral bending moment must be resisted, while both the net twisting moment and the net extension moment must be balanced among the three muscles to zero value. The fibers of these muscles are not vertical, so their contraction forces have horizontal components. Among these components, the horizontally directed external load and the two shear resistances of the motion segment, all horizontal forces are equilibrated. Because body segment weights have been ignored, the compression on the spine is only that needed to equilibrate the vertical components of the muscle contraction forces.

Example 5: Resisting a Longitudinal Twist Moment. A final example concerns the internal forces developed when a pure 20 Nm twisting moment to the left must be resisted. Ignoring body segment weights, the net reaction consists only of the 20 Nm resistance moment. Using the same geometrical data and solution procedure, the internal forces are found to be

$$C = 194\text{ N} \quad S_r = 78\text{ N} \quad I_r = 56\text{ N}$$
$$S_a = -37\text{ N} \quad L_r = 111\text{ N}$$
$$X_l = 108\text{ N}$$

and other model internal forces have zero value.

This solution has a character similar to the previous one, except that now the twisting moment to be resisted has a nonzero value, while the net lateral bending and extension moments must be balanced to zero value.

VALIDATION OF INTERNAL FORCE ESTIMATES

The foregoing explanations show that, while there is little ambiguity about the nature of the net reactions, major assumptions are used in the estimation of the internal forces. Before the proposed calculation schemes can be used with confidence, the assumptions made need to be validated by experimental measurement.

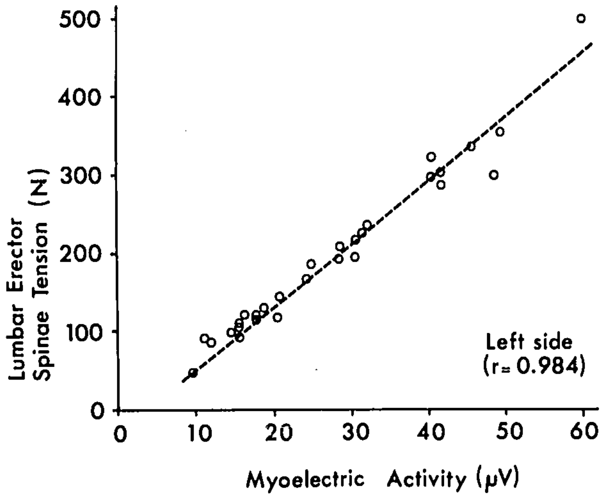
Direct measurement of trunk internal forces *in vivo* is impractical, but there are at least two means to determine internal forces indirectly in the laboratory; by measurement of intradiscal pressures and by measurement of myoelectric activity. In papers included in this volume, Nachemson[7] reviews the evidence showing that intradiscal pressure measurements are indicative of compression loads on the spine, and Ortengren, Andersson, and Nachemson[8] review the evidence showing that myoelectric activity in the back muscles relates monotonically to the muscle contraction forces and to the disc pressures.

Using these two measurement techniques, we have made a series of studies in our laboratories that have amply validated the spine load calculation schemes presented here in a number of circumstances. Good agreement between computed erector muscle tensions and erector muscle myoelectric activities over a range of weight-holding tasks executed while sitting at a table is reported by Andersson et al[1] and over a range of sagittally symmetric standing work tasks is reported by Schultz et al.[11] Schultz et al[12] report good agreement in both kinds of tasks between predicted spine compression and spine compression determined from intradiscal pressure measurements. Figures 4 and 5 summarize some of those data. The agreement has been confirmed over a wide range of loads on the spine, tensions in the back muscles, and types of activities.

Despite these experimental validations of the load estimation schemes, caution is still needed in interpreting computed estimates of trunk internal forces. It is not yet clear what objective functions should be used to solve statically indeterminate problems of internal force estimation in certain circumstances. Ongoing research seems to indicate that neither spine compression estimates nor posterior back muscle tension estimates of when those muscles are called upon are very sensitive to objective function choice over a range of physiologically reasonable schemes. Moreover, objective function choice seems not very important in maximal exertions; every muscle that can contribute to these will be called upon to contribute at maximum or near-maximum intensity no matter what the objective function is. But in submaximal physical efforts which tend to extend or to laterally bend the trunk, different objective functions can yield significantly different estimates of muscle tensions. More research is needed to determine what choices the neuromuscular system makes when it has several options available for task execution.

EXTENSION TO DYNAMIC PROBLEMS

Execution of a physical activity is sometimes called dynamic if it is accompanied by body motion of any kind. However, many activities involving body motion can be analyzed without significant error as if they were static. Dynamic considerations are important mechanically only when a motion involves significant linear or angular accelerations. The product of a mass and its linear acceleration is called an inertial force; the product of a moment of inertia and its angular acceleration is called an inertial moment. In a biomechanical analysis, body dynamics need to be considered only when the inertial forces and the inertial moments produced are of



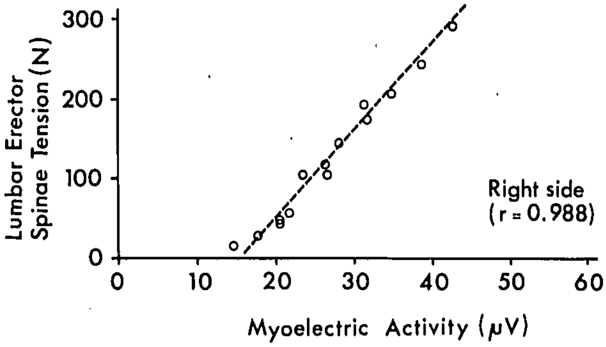


Fig. 4. Predicted erector muscle tensions compared with myoelectric activity in these muscles on the right and left sides. Mean data from ten subjects. These were weight-holding tasks executed while sitting at a table. Each circle corresponds to a different arm position or a different amount of weight held. The data points are correlated by the regression lines shown, with a correlation coefficient of 0.98 on the left side and 0.99 on the right side. From Schultz et al.[9]

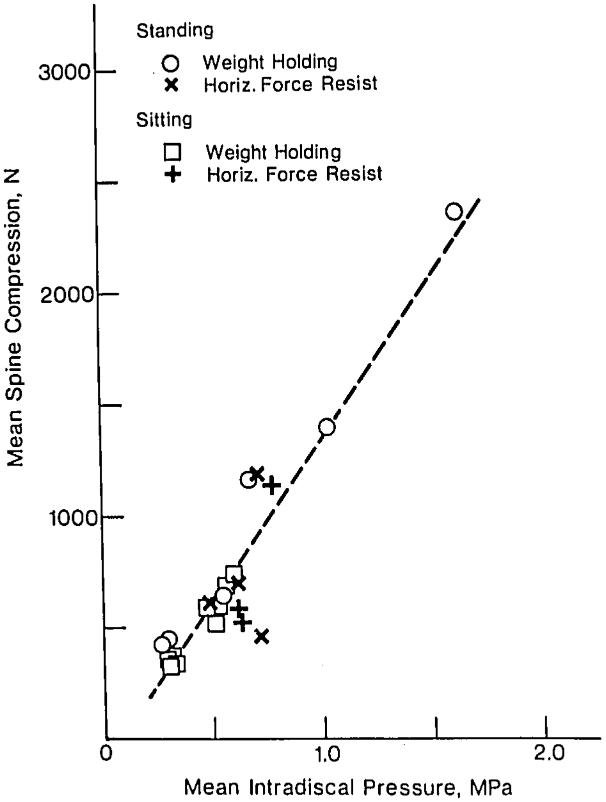


Fig 5. Predicted spine compression versus measured intradiscal pressure at the L3 disc. Intradiscal pressures are proportional to spine compression. Each data point corresponds to a different activity: resisting horizontal forces while sitting or standing, and weight-holding while sitting, standing with the trunk upright, or standing with the trunk flexed. The data points are correlated by a regression line, with a correlation coefficient of 0.91. From Schultz et al.[12]

magnitudes that are significant when compared with the forces and moments needed for equilibrium. If the inertial forces and moments are small when compared with the forces and moments that would be required for static equilibrium, an activity involving body motion can safely be analyzed as a quasi-static activity.

In truly dynamic activities in which significant inertial forces and moments do arise, these forces and moments can be accounted for easily enough. First, the inertial forces and moments need to be computed. This can be done through measurement or estimation of the appropriate linear and angular accelerations and use of anthropometric data on body segment masses, mass centers, and moments of inertia. Once the inertial forces and moments are determined, they are applied at the body segment mass centers as if they were additional external forces. The remaining procedures we have outlined are then executed without alteration. In other words, the inertial forces and moments will directly enter the procedures used to calculate the net reaction but not those used to estimate the internal forces, under almost all circumstances of practical interest.

Few quantitative studies of dynamic effects in nonathletic physical activities are available. Evaluations of the importance of dynamics in ordinary activities still need to be made.

REFERENCES

1. Andersson GBJ, Örtengren R, Schultz A: Analysis and measurement of the loads on the lumbar spine during work at a table. J Biomech 13:513–520, 1980
2. Berkson MH, Nachemson A, Schultz AB: Mechanical properties of human lumbar spine motion segments— Part II: Responses in compression and shear; influence of gross morphology. J Biomech Eng 101:53–57, 1979
3. Clauser C, McConville J, Young J: Weight volume and center of mass of segments of the human body. AMRL-TR-69-70, Wright-Patterson Air Force Base, Ohio 1969
4. Dantzig GB: Linear Programming. New York, McGraw-Hill Book Company, 1968
5. Eycleshymer AC, Schoemaker DM: A Cross-section Anatomy. New York, Appleton-Century-Crofts, 1911
6. Morris JM, Lucas DB, Bresler R: Role of the trunk in stability of the spine. J Bone Joint Surg 43A:327–351, 1961
7. Nachemson AL: Disc pressure measurements. Spine 6:93–97, 1981
8. Örtengren R, Andersson GBJ, Nachemson AL: Studies of relationships between lumbar disc pressure, myoelectric back muscle activity, and intra-abdominal (intragastric) pressure. Spine 6:98–103, 1981
9. Örtengren R, Andersson GBJ: Electromyographic studies of trunk muscles, with special reference to the lumbar spine. Spine 2:44–52, 1977
10. Schultz AB, Warwick DN, Berkson MH, Nachemson AL: Mechanical properties of human spine motion segments. Part I: Responses in flexion-extension, lateral bending, and torsion. ASME J Biomech Eng 101:46–52, 1979
11. Schultz AB, Andersson GBJ, Örtengren R, Björk R, Nordin M: Analysis and quantitative myoelectric measurements of loads on the lumbar spine when holding weights in standing postures. Spine (In press)
12. Schultz AB, Andersson GBJ, Örtengren R, Nachemson A, Haderspeck K: Loads on the lumbar spine: validation of a biomechanical analysis by measurements of intradiscal pressures and myoelectric signals (Unpublished manuscript)
13. Seireg A, Arvikar RJ: A mathematical model for evaluation of forces in lower extremities of the musculo-skeletal system. J Biomech 6:313–326, 1973

Address reprint requests to

Albert B. Schultz, PhD
Department of Materials Engineering
University of Illinois at Chicago Circle
Box 4348
Chicago, IL 60680

Accepted for publication May 5, 1980.