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Dynamic Forces Acting on the Lumbar Spine During Manual Handling

Can They be Estimated Using Electromyographic Techniques Alone?

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Study Design. Compressive loading of the lumbar spine was analyzed using electromyographic, movement analysis, and force-plate techniques.

Objectives. To evaluate the inertial forces that cannot be detected by electromyographic techniques alone.

Summary of Background Data. Links between back pain and manual labor have stimulated attempts to measure spine compressive loading. However, direct measurements of intradiscal pressure are too invasive, and force plates too cumbersome for use in the workplace. Electromyographic techniques are noninvasive and portable, but ignore certain inertial forces.

Methods. Eight men lifted boxes weighing 6.7 and 15.7 kg from the ground, while joint moments acting about L5–S1 were quantified 1) by using a linked-segment model to analyze data from Kistler force plates and a Vicon movement-analysis system, and 2) by measuring the electromyographic activity of the erector spinae muscles, correcting it for contraction speed and comparing it to moment generation during static contractions. The linked-segment model was used to calculate the "axial thrust," defined as the component of the L5–S1 reaction force that acts along the axis of the spine and that is unrelated to trunk muscle activity or static body weight.

Results. Peak extensor moments predicted by the two techniques were similar and equivalent to spinal compressive forces of 2.9–4.8 kN. The axial thrust "hidden" from the electromyographic technique was negligible during slow lifts, and remained below 4% of peak spinal compression even during fast heavy lifts. Peak axial thrust was proportional to the peak vertical ground reaction ($R^2 = 0.74$).

Conclusions. Electromyographic techniques can measure dynamic spinal loading, but additional force-plate data would improve accuracy slightly during lifts requiring a vigorous upward thrust from the legs. [Key words: compressive loading, electromyography, inertial forces, linked-segment model, lumbar spine] **Spine 1999;24:698–703**

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Close links between back disorders and heavy manual labor[9,12] have stimulated attempts to measure and regulate spine compressive loading in the workplace. This is a difficult task because most of the compressive force on the spine comes from tension in the muscles of the back and abdomen as they stabilize and move the trunk,[7,8,16,18] and the associated muscle activity varies greatly with posture and speed of movement.

The only gold standard measurements of spine compressive loading are those performed by Nachemson,[17] who introduced a long pressure-sensitive needle into the lumbar discs of living volunteers. Unfortunately, this technique is invasive and cannot be used during vigorous dynamic movements, which are precisely the activities that load the spine most.[7,13]

Other methods of measuring spinal loading fall into two basic categories: 1) those that measure the acceleration of body parts and use a linked-segment model to infer net moments acting about the joints,[2–4,10] and 2) those that attempt to measure muscle forces directly by calibrating electromyographic (EMG) signals against force generation.[5,14,15] Some hybrid techniques combine linked-segment models with EMG, using the EMG data to apportion joint moments between different muscles in order to calculate joint reaction forces.[18]

The two basic approaches incorporate assumptions and approximations that make it difficult to assess their accuracy except in quasi-static postures wherein their predictions can be compared with those of Nachemson.[17] Consequently, there remains considerable uncertainty over how large spine compressive loading really is during vigorous activities.

Much of this uncertainty would be dispelled, however, if the two preceding noninvasive approaches yielded similar values. These approaches, based on fundamentally different assumptions and approximations, are subject to different sources of error. Therefore, it is unlikely (but not impossible) that the techniques would yield similar estimates of joint loading if systematic errors in either or both techniques were large. For this reason, the current authors applied both approaches simultaneously and independently to calculate spine loading when young men made vigorous lifts in the laboratory. The three-dimensional linked-segment model of Kingma et al,[10] which uses input data from two force plates and a four-camera Vicon system, was compared with the EMG technique of Dolan and Adams,[5] in which EMG signals are related to extensor moment generated during isometric contractions, with correction factors applied to account for the effects of muscle length and contraction velocity on the force–EMG relationship.

This study showed that the joint moments at L5–S1 predicted by the two techniques were generally in good agreement (Toussaint et al, unpublished results), although the EMG technique yielded slightly higher values and showed more intersubject variation, possibly because of differences in muscle recruitment patterns. Overall, the results increased confidence in the ability of both techniques to measure peak spinal loading without large systematic errors.

Further analysis of these results, however, suggested that certain forces were "hidden" from each technique. The linked-segment model calculated only the net joint moments and was therefore unable to detect whether any opposing moment was being generated by antagonistic muscle activity. However, the EMG technique failed to detect inertial forces acting along the axis of the spine. The current study attempted to quantify the inertial forces "hidden" from simple EMG models that rely solely on EMG recordings from trunk muscles, and to compare them with forces attributable to trunk muscle action. The purpose was to indicate the applicability limits of EMG-based techniques for measuring fully dynamic loading of the lumbar spine.

■ Materials and Methods

Participants. Eight healthy young men volunteered for the study. They were 21 to 36 years of age (mean, 26 years), and their body mass ranged between 63 and 81 kg (mean, 72 kg).

Lifting Tasks. Participants lifted a wooden box containing metal weights from a platform 10 mm above the ground. They started the lift in either a bent-leg or straight-leg position with their hands grasping a handle on either side of the box, and ended in the static upright standing position with the load at knuckle height. A large number of lifts were performed (Toussaint et al, unpublished results), but the data analyzed in detail here are for sagittal-plane lifts of 6.7 and 15.7 kg, made with the knees either straight or flexed, and performed to the beat of a metronome at either the 1.0-second ("fast") or 1.5-second ("slow") setting. An electrical switch was activated when the box left the ground, and this signal defined time 0 for all measurements.

These lifts were studied because the amount and speed of knee extension and the magnitude of the load being lifted were expected to have the greatest influence on the inertial compressive force exerted by the legs on L5–S1 (see later discussion). Trunk asymmetry may influence the moments acting at the lumbosacral joint, but is unlikely to have a marked effect on the inertial forces unrelated to trunk muscle activity or static body weight. Therefore, for simplicity only sagittal plane lifts were studied.

Linked-Segment Model Technique. Full details of this technique are reported elsewhere.[10] The ground reaction force under each foot was recorded at 60 Hz by two Kistler force plates.

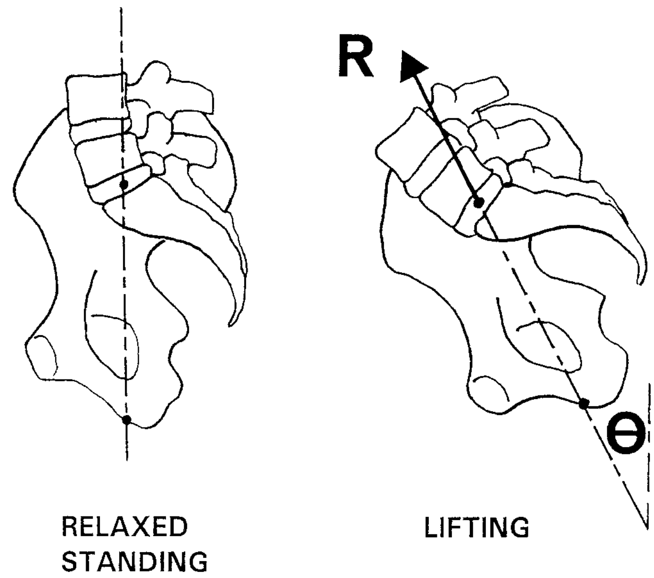


Figure 1. During lifting, the pelvis is rotated by a variable angle θ in the sagittal plane, where θ is defined as 0 during relaxed standing. The linked-segment model, besides calculating the net moment, also calculates the reaction force acting at the L5–S1 joint, and the component of this force acting upward in the rotated frame of the pelvis is denoted by R. R represents the upward force from the legs and pelvis on the trunk segment, but it does not include the additional forces arising from tension in muscles, fascia, and ligaments that span L5–S1. In static postures, R must balance a component of the upper body weight and the weight being lifted. It is convenient to define the axial thrust from the legs as follows: Axial thrust $= R - (B + W) \cos \theta$, where B = weight of body above L5–S1, and W = weight lifted.

The three-dimensional position of reflective markers attached to the participant were measured simultaneously by a four-camera Vicon system (Oxford Metrics, Ltd., Oxford, Oxon, UK) operating at 60 Hz. Markers were attached to the feet, lower legs, upper legs, and pelvis using specially constructed braces.

To calibrate the system before the experiments, additional markers were placed on certain bony landmarks to allow reconstruction of an anatomic axis system. The force plate and Vicon data were incorporated into a validated fully dynamic three-dimensional linked-segment model, which computed net joint reaction forces and net joint moments. Calculations started at the feet and progressed upward. In the current study, the vertical reaction forces from the two force plates were added together.

Axial Thrust. Of particular interest in the current study was the component of the reaction force at the L5–S1 joint that acts along the axis of the lumbar spine, as shown in Figure 1. This joint reaction (R) represents the force from the legs and pelvis acting on the trunk segment, but does not include the spinal compressive force arising from the activity of trunk muscles (or from tension in ligaments) that span the L5–S1 joint. (The total compressive force on the lumbar spine is the sum of the trunk muscle and reaction forces.) In static equilibrium, R must balance a component of the upper body and box weights combined, $(B + W)\cos\theta$ in Figure 1. If this static gravitational component is subtracted from R during dynamic activities, then the remaining force is a measure of the inertial compressive force exerted by the legs on L5–S1. This force is termed *axial thrust* in the current study.

The axial thrust has two main characteristics: 1) It falls to 0 in static postures, and 2) it is independent of the activity of muscles spanning the L5–S1 joint. The second characteristic means that the axial thrust will be undetected by EMG-based techniques that record only from the back and abdominal muscles. It should be noted that the axial thrust acts along the longitudinal axis of the lumbar spine (Figure 1), but that it is not exactly perpendicular to the midplane of any particular disc.

Electromyographic Technique for Measuring Extensor Moment. Full details of this technique were published previously.[5] Four pairs of EMG electrodes (Biolect, Ramsbury, Wilts., UK) were attached to the skin surface overlying the erector spinae muscles at the levels of T10 and L3 on both sides of the midline, and a reference electrode was attached over the sternum. Careful skin preparation ensured that the resistance between the reference and recording electrodes was always less than 10 kΩ, and often less than 5kΩ, and this in turn ensured that the signal-to-noise ratio was high. The EMG signals were full-wave rectified and electronically averaged with a time constant of 50 milliseconds. They were then sampled at 60 Hz, A–D converted, and stored on a computer for analysis. The curvature of the lumbar spine, which determines the length of the erector spinae muscles, was measured at 60 Hz using the 3 space Isotrak device (Polhemus, Colchester, VT).[6] This device consists of a source of pulsed electromagnetic waves that was attached to the skin overlying the sacrum and a small sensor of these waves that was attached to the skin overlying the spinous process of L1. Changes in lumbar curvature measured with a similar-size device were previously compared with angular movements of L1 on the sacrum as measured by plain radiographs,[1] and excellent correlation between the two was found (r = 0.91).

To calibrate EMG signals against extensor moment, each participant was positioned in a postural-restraint frame and instructed to pull upward on a floor-mounted load cell, with increasing force, to reach a maximum after 3 seconds. The EMG activity averaged from the four electrode sites was related linearly to extensor moment as calculated from the load cell data.[5] The EMG-extensor moment calibrations were repeated approximately 10 times, with the participant positioned in different postures. For each participant, regression analysis was used to express the gradient and intercept of the 10 EMG-extensor moment graphs as variable functions of muscle length (*i.e.,* lumbar curvature as measured by the Isotrak).

The EMG signals recorded during the dynamic lifts were corrected first for electromechanical delay, and for muscle contraction velocity (as indicated by the rate of change of lumbar curvature). The correction factor for contraction velocity was determined in an earlier study,[5] in which healthy participants performed extensions of the trunk over a range of different speeds from 0° to 90°/sec on an isokinetic (Cybex International, Inc., Medway, MA) dynamometer. Erector spinae muscle length was assumed to be represented by the lumbar curvature between L1 and S1 as measured by the Isotrak. During the trunk extensions, the rate of lumbar curvature change was calculated and its influence on the EMG–torque relationship determined across the range of velocities studied. During concentric contractions, the EMG–torque ratio (E) was found to increase with the rate of change in lumbar curvature as compared with the isometric condition (Eo). This effect was best described by the following equation:

$$Eo = E/(1 + A d\theta/dt)$$

where $d\theta/dt$ is the rate of change in lumbar curvature.

The gradient of this relationship (A) was influenced by muscle length according to the equation $A = 0.0014 * e^{0.045*P}$, where P is the lumbar curvature (at any given time) expressed as a percentage of the participant's range of flexion. In the current study, the effects of contraction speed were accounted for by applying these equations to the dynamic EMG signal. Corrected EMG values were then compared with the static calibrations (for the appropriate lumbar curvature or muscle length) to calculate extensor moments.[5] The extensor moment includes components attributable to tensile forces in noncontractile tissue in both muscle and structures such as lumbodorsal fascia, supraspinous ligament, and the intervertebral discs and ligaments.

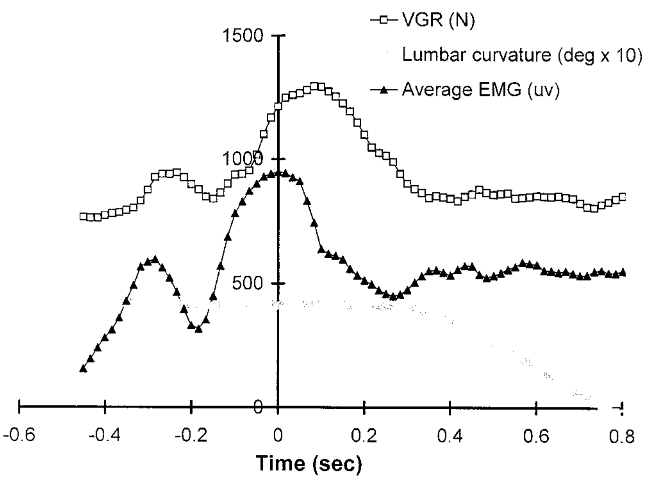


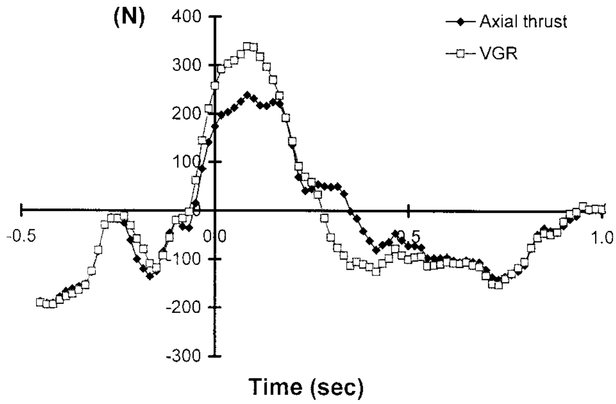
Figure 2. Raw data for a fast bent-leg lift of 15.7 kg, showing vertical ground reaction (VGR) force, curvature of the lumbar spine as measured by the 3Space Isotrak (Polhemus, Colchester, VT), and electromyographic (EMG) activity of the erector spinae (averaged from four sites). Time 0 was defined as the instant the box left the ground. Note that there is considerable muscle activity and an increasing VGR before the box leaves the ground, and that the lumbar spine does not begin to extend until after the main VGR and EMG peaks are over. The time lag between the VGR and EMG peaks is attributable mostly to the electromechanical delay between electrical activation of muscle and mechanical force generation.

Statistical Methods. The effects of weight, lifting style, and lifting speed on the inferred peak values of axial thrust were examined using analysis of variance. The correspondence between peak values of vertical ground reaction (VGR) and thrust (given by the VGR–thrust ratio) in straight-leg and bent-leg lifts was compared using matched-pair *t* tests. Linear regression was used to characterize the dependence of peak values of axial thrust on the peak VGR force. Statistical significance was accepted at the 5% level.

■ Results

Raw data for a typical lift are shown in Figure 2. The figure shows that the downward push on the force plates,

(A)



(B)

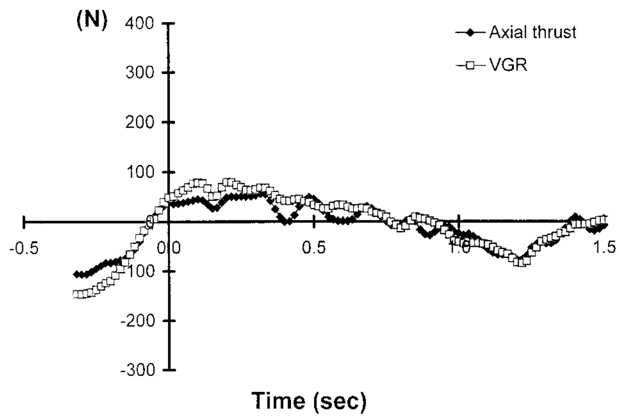


Figure 3. Comparisons between the vertical ground reaction (VGR) force and the axial thrust from the legs acting on the lumbar spine during lifts of 15.7 kg. The combined static weight of participant (complete with braces) and box has been subtracted from the VGR to make it comparable to the thrust, as defined in Figure 1. Before liftoff, the box was resting on the ground in front of the force plate. This explains why VGR and axial thrust have negative initial values approximately equal to the weight of the box (154 N), which has not yet been taken into the hands. In a fast bent-leg lift **(A)**, the axial thrust approaches 250 N and corresponds closely to the VGR. However, in a slow straight-leg lift **(B)**, the axial thrust is considerably lower.

and back muscle activity, started before the weight left the ground (time 0). Consequently, force generation by the back muscles, which occurs approximately 70 to 90 milliseconds after the onset of back muscle activity,[5] also preceded the lifting of the weight, even though the lumbar spine did not begin to extend until slightly later.

The axial thrust from the legs, calculated as described in Figure 1, is compared in Figure 3 with the VGR force during two lifts. (The VGR was chosen for comparison rather than the resultant ground reaction because the former can be quantified by relatively simple techniques.) The combined static weight of participant and box was subtracted from the VGR to make it comparable with the thrust. Because of this, VGR and axial thrust have negative values before liftoff (Figure 3) approximately equal to the weight of the box (154 N), which was resting on the ground in front of the force plate. During both lifts, the axial thrust varied with the ground reaction force and approached 0 in the static upright position at the end of the lift. The peak axial thrust was much greater in the fast bent-leg lift than in the slow, straight-leg lift.

For each participant and each lift, the peak axial thrust was calculated, and average values are compared for the four different lifts in Figure 4. Peak values increased significantly with lifting speed and were higher in bent-leg than straight-leg lifts. However, the effect of load was not significant ($F = 0.383$; $df = 1$), and this was true even if bent-leg lifts alone were considered ($F = 0.306$; $df = 1$). During slow straight-leg lifts of 6.7 kg, the axial thrust reached 56 ($\pm$32) N, but in the fast bent-leg lifts of 15.7 kg, it rose to 170 ($\pm$89) N on average. For comparison, the peak extensor moment in each of the bent-leg lifts, as measured by the EMG technique, varied between 204 and 323 Nm, respectively (Figure 5). If it is assumed that the equivalent lever arm of the back muscles and fascia is between 6.5 and 7.5 cm, depending on the size of the participant,[5] then the peak compressive force acting on L5–S1 during these lifts, according to the EMG technique, averaged 2.9 and 4.8 kN, respectively. Therefore, the axial thrust represents less than 4% of the estimated spinal compressive force during the range of lifts examined in this study. The highest individual axial thrust calculated for any participant was 381 N, and this corresponded to 9% of the peak spinal compressive force derived from that participant's EMG data.

Figure 6 shows that the axial thrust on the lumbar spine is closely related to the vertical component of the ground reaction force. The correspondence between the peak values of axial thrust and ground reaction showed no significant dependence on whether the legs were bent (this statement is true of peak values only). For pooled data, Rsq = 0.74.

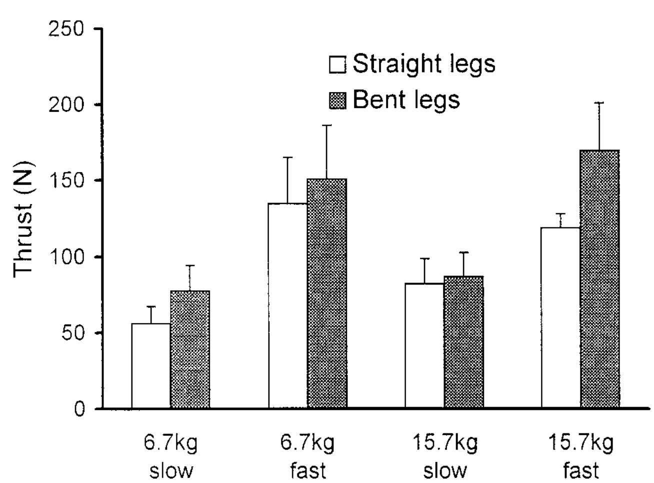


Figure 4. Peak values of the axial thrust acting on L5–S1 are compared for the different lifts. Bars indicate the SEM (n = 8). The thrust was greater in fast lifts than in slow lifts ($P < 0.0001$), and in bent-leg lifts than in straight-leg lifts ($P < 0.05$).

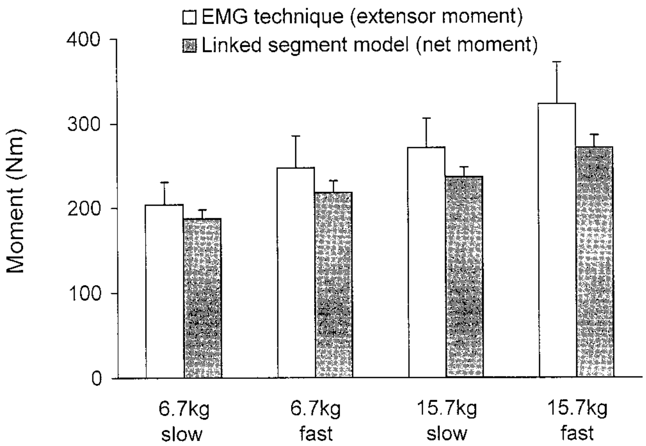


Figure 5. Peak joint moments acting about L5–S1 during the four different bent-leg lifts. The total extensor moment calculated by the electromyographic (EMG) technique is compared with the net extensor moment calculated by the linked-segment model. Error bars indicate the SEM ($n = 8$). Extensor moments of this magnitude imply that peak compressive loading of the lumbar spine was in the region of 2.9 to 4.8 kN.

Discussion

This experiment showed that lifting weights from the ground leads to an inertial force acting up the axis of the lumbar spine as a result of the upward thrust from the legs. The magnitude of this axial thrust varies from approximately 56 N when a 6.7-kg box is lifted slowly to 170 N on average when a 15.7-kg box is lifted quickly. These results apply to sagittal-plane lifts, but similar results might be expected in asymmetric lifting because rotation of the trunk is unlikely to have a large effect on the thrust exerted by the legs. The good linear relationship between peak values of axial thrust and VGR force indicate that the upward thrust of the legs on the trunk is to a certain extent mirrored by the downward thrust of the feet on the force plate. Therefore, peak values of axial thrust can be predicted from measurements of VGR without the need for complex motion analysis data and linked segment models (Figure 6).

The compressive force acting on an intervertebral disc generally is considered to be the force that acts perpendicular to the midplane of that disc. Therefore, disc compression arising from the axial thrust will be somewhat less than the thrust itself. Disc compression could be calculated by multiplying the thrust by the sine of the (acute) angle between the midplane of the disc in question and the line of action of the thrust as defined in Figure 1, but these angles were not measured in the current study. For this reason, the compressive force on L5–S1 arising from the axial thrust will be somewhat less than the average value of 4% calculated earlier.

It is not surprising that the axial thrust should be higher in rapid lifts because the upper body is subjected then to higher accelerations by the legs, which must raise it through the same vertical distance in a shorter time. Similarly, the thrust is higher in bent-leg lifts because these require the legs to raise the center of gravity of the whole body in an approximately vertical direction. The small axial thrusts in the straight-leg lifts probably are associated with slight but rapid vertical movements of the pelvis as the knees become "locked" straight when the weight is lifted. (Knees rarely were completely straight at the outset of even the "straight-leg" lifts.) The predicted intercept on the x-axis in Figure 6 implies that the axial thrust would be negligible during gentle lifts in which the VGR force did not exceed body weight by more than approximately 20 N. In the current study, the lowest values of VGR were observed in the slow straight-leg lifts of 6.7 kg (Figure 3B), but, even in these lifts, the peak VGR always exceeded body weight by at least 60 N.

The axial thrust is caused by forces exerted on the trunk segment by the muscles of the legs and pelvis. Therefore, by definition, the axial thrust is unrelated to the activity of muscles spanning the L5–S1 joint, so it cannot be detected by EMG electrodes on the back or abdomen. However, the largest forces acting on the lumbar spine come from the back muscles as they generate an extensor moment to bring the upper body into the upright position. Antagonistic forces from the abdominal muscles also compress the spine, both directly and because the resulting flexor moment increases the required extensor moment. However, these forces are small in flexed postures,[16] becoming substantial only in upright and semi-upright postures in which they account for 10% to 45% of the total compressive force, depending on the speed of lifting.[8] The greater part of this increase in spinal compression will be caused by the reactive extensor moment because the erector spinae muscles have a shorter lever arm about the L5–S1 disc than the flexor muscles. These latter forces would be detected by the EMG model used in the current study and may partly explain the higher calculated moments obtained with the EMG technique compared with the linked segment

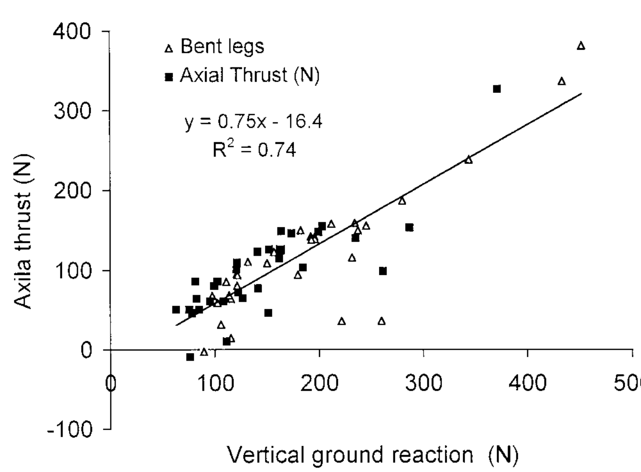


Figure 6. Peak values of inertial thrust were proportional to peak values of the vertical component of the ground reaction (VGR). This correlation was little influenced by whether the legs were bent or straight, so data were pooled for regression analysis. (The combined static weight of participant and box was subtracted from the VGR to make it comparable with the thrust).

model (Figure 5). However, spinal compression resulting directly from abdominal muscle tension would not be detected. Recent results from the authors' laboratory suggest that in sagittal-plane lifts of low to moderate loads, these forces account for approximately 8% of the total spinal compressive force, with values less than this in more flexed postures.[11]

In summary, back muscle forces can be quantified directly from EMG recordings, provided corrections are applied to account for the electromechanical delay and for changes in muscle length and contraction velocity.[5] Compressive forces arising directly from abdominal muscle activity, which were not included in the measurements made in this study, would be expected to account for less than 8% of total spinal compression in the flexed postures examined in the current study.

In upright postures, however, higher values of abdominal activity might be expected,[8] especially where some degree of rotation is involved, in which case predictions of spinal compressive loading would be improved by including direct measurements of abdominal muscle activity. The axial thrust, which was unrelated to trunk muscle EMG, accounted for less than 4% of the total compressive force acting on L5–S1, suggesting that it can be ignored during the range of lifting tasks considered in this study. Even during the most vigorous lifts performed by any participant, the axial thrust still remained below 10% of the peak spinal compressive force, and it could be estimated accurately from the VGR.

The lifting of heavier loads at faster speeds, such as occurs in competitive weight lifting, would result in higher inertial forces than those reported in the current study. However, in the workplace, where directives on manual handling are applicable, the loads and speed of lifting usually are in the region of those used in the current study, so the magnitude of the inertial forces should be comparable.

It can be concluded from this study that simple EMG techniques based on recordings of trunk muscle activity are suitable for the assessment of fully dynamic spinal loading in the workplace, with the reservation that additional force-plate data would improve accuracy slightly during the most arduous lifts.

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