Research Report

The Relationship Between Lumbar Spine Load and Muscle Activity During Extensor Exercises

Background and Purpose. There have been no previous studies that quantitatively assessed the load on the spine during extensor exercises. The purpose of our study was to investigate the loading of the lumbar spine and trunk muscle activity levels while subjects performed typical trunk extensor exercises. **Subjects.** Thirteen male volunteers (mean age=21.0 years, SD=1.0, range=19–23; mean height=176.0 cm, SD=6.2, range=165–188; mean mass=77.0 kg, SD=7.0, range=63–89) participated. **Methods.** The subjects performed four different back exercises. Electromyographic (EMG) activity was recorded from 14 trunk muscles. The postures that corresponded to the maximum external moment were identified and quantified using rigid body modeling combined with an EMG-driven model to determine joint loading at the L4-5 joint. The exercises were then evaluated based on the lumbar spine loading and peak muscle activity levels. A reference task of lifting 10 kg from midthigh was included for comparison. **Results.** The exercises involving active trunk extension produced the highest joint forces and muscle activity levels. Exercises involving leg extension with the spine held isometrically demonstrated asymmetrical activity of the trunk muscles, thereby reducing loads on the spine. **Conclusion and Discussion.** The back extensor exercises examined provided a wide range of joint loading and muscle activity levels. Single-leg extension tasks appear to constitute a low-risk exercise for initial extensor strengthening, given the low spine load and mild extensor muscle challenge. When combined with contralateral arm extensions, the challenge and demand of the exercise were increased. The compressive loading and extensor muscle activity levels were highest for the trunk extension exercises. [Callaghan JP, Gunning JL, McGill SM. The relationship between lumbar spine load and muscle activity during extensor exercises. *Phys Ther.* 1998;78:8–18.]

Key Words: *Electromyography, Extensor exercise, Injury, Lumbar spine, Rehabilitation.*

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Low back extensor exercises are used for a variety of reasons, but mainly for rehabilitation of the injured low back, prevention of injury, and as a component of fitness training programs to enhance performance levels. The objective of exercise is often to place stress on both damaged and healthy supporting tissues to foster tissue repair and strengthening while avoiding excessive loading that can exacerbate existing structural weakness. From our experience, many traditional extensor exercises generate high spinal loads as a result of externally applied compressive and shear forces (either from free weights or resistance machines). Although knowledge of tissue forces is important to avoid further injury, little work has been performed to quantify these forces during trunk exercises. The overall objective of our research was to examine the load on the low back together with muscle activity levels during typical back extensor exercises.

The reported effectiveness of various training and rehabilitation programs for the low back is quite variable, with some authors claiming great success but other authors reporting no, or even negative, results.[1,2] The cause of this tissue damage has been attributed to excessive spine flexion,[3–5] disadvantageous muscle lengths in some postures,[6] or inappropriate orientation of internal structures of the torso with respect to the legs.[7] The contradictory findings regarding the effectiveness and safety of exercise programs in various reports[8] may be due to the prescription of inappropriate exercises. Specifically, a poorly selected exercise could exacerbate an existing injury by excessively loading the damaged structure.

Although some exercises for the low back have been recommended for their capacity to maximize muscle activity,[9,10] virtually none have been examined by analyzing the forces they generate on the spine. Fortunately, sophisticated techniques are being developed that facilitate investigation of the loads that lead to injury in a variety of possible injury sites. Knowledge of the tissue loads is necessary to permit the testing of hypotheses designed to reduce the risk of injury, from a preventative standpoint, and to optimize the loading that results from various rehabilitation programs for the injured.

The purpose of our research was to quantitatively identify exercises that optimized the challenge to extensor muscles, which stabilize and support the low back, while simultaneously placing minimal load on the lumbar spine. We hypothesized that some low back extensor exercises result in higher extensor muscle activity levels but lower lumbar spine loading due to the lack of muscle co-contraction.

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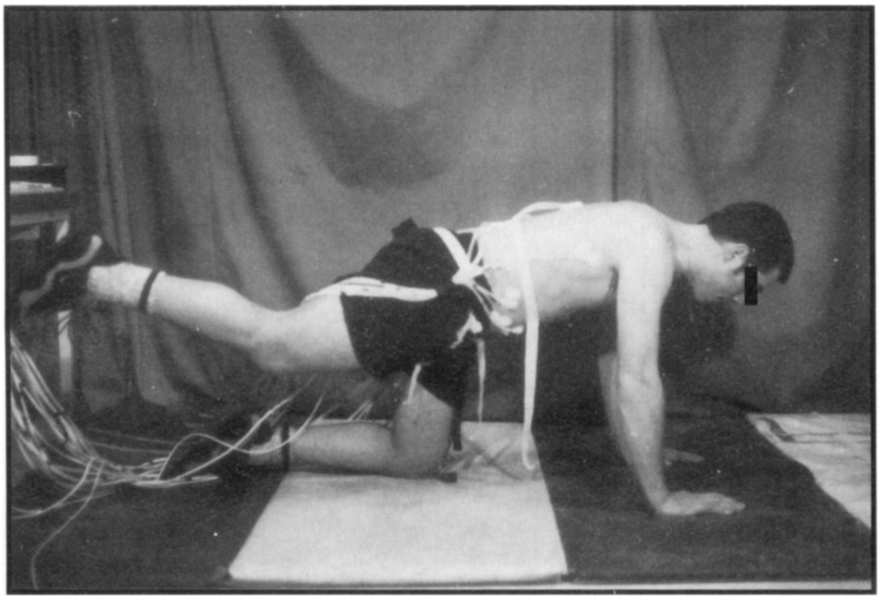

Figure 1.
Exercises 1 and 2 involved extension of the leg to the horizontal. The exercise was performed for both legs (right leg extension and left leg extension). The posture shown was chosen as representing the most challenging instant.

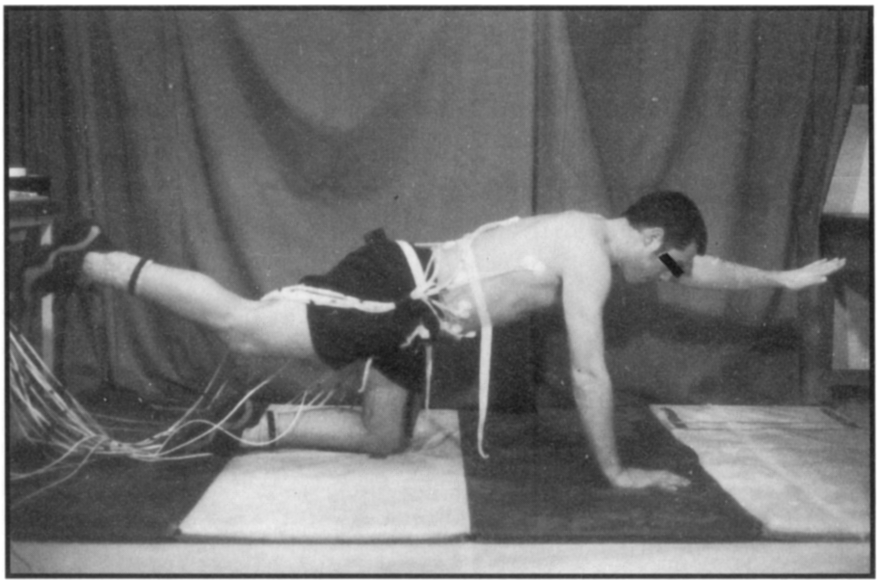

Figure 2.
Exercises 3 and 4 involved extension of the contralateral arm combined with leg extension. The posture shown was used to represent the instant of peak loading. Both sides of the body were exercised (right leg and left arm extension and left leg and right arm extension).

Method

Subjects

Thirteen male volunteers were recruited from a university student population (mean age=21.0 years, SD=1.0, range=19–23; mean height=176.0 cm, SD=6.2, range=165–188; mean mass=77.0 kg, SD=7.0, range=63–89). None of the subjects had experienced any low back pain for a minimum of 1 year. Therefore, whether patients with low back pain would perform the exercises similarly and have similar muscle activity and load levels was not studied. Informed consent was obtained from all subjects.

Instrumentation

Fourteen pairs of Medi-Trace disposable silver-silver chloride surface electromyogram (EMG) electrodes* were applied to the skin bilaterally over the following muscles: rectus abdominis, 3 cm lateral to the umbilicus; external oblique, approximately 15 cm lateral to the umbilicus; internal oblique, below the external oblique electrodes and just superior to the inguinal ligament; latissimus dorsi, lateral to T-9 over the muscle belly; thoracic erector spinae, 5 cm lateral to the T-9 spinous process; lumbar erector spinae, 3 cm lateral to the L-3 spinous process; and multifidus, 3 cm lateral to the L-5 spinous process.[11] Prior to data collection, all subjects performed maximal isometric contractions for all monitored muscle groups to allow EMG normalization. Procedures for obtaining maximum EMG activity for normalization have been explained previously by McGill.[12] Briefly, three tasks were used to elicit maximum EMG activity from the 14 recorded sites. The abdominal muscle groups were recruited with a modified bent-knee sit-up, the trunk extensors were activated by cantilevering the trunk over the end of the bench, and the latissimus dorsi muscle was recruited with a simulation of a lateral pull-down exercise. All three maximal effort tasks were performed against an equal resistance (isometric) supplied by the experimenter. The raw EMG signal was prefiltered to produce a bandwidth of 20 to 500 Hz and amplified with a differential amplifier (common-mode rejection ratio greater than 90 dB at 60 Hz and input impedance greater than 10 MΩ above 1 Hz) to produce peak-to-peak amplitudes of approximately 2 V. The amplified signal was analog-to-digitally (A/D) converted at 1,024 Hz.

A sagittal view of each subject's right side for all trials was recorded on videotape, at a frame rate of 30 Hz, to allow

* Graphic Controls Canada Ltd, 215 Hebert St, Gananoque, Ontario, Canada K7G 2Y7.

flexion and extension moments about the L4-5 joint to be calculated. A transverse-plane view was also recorded for two exercises (single-leg extensions) to allow the twist moment about the L4-5 joint to be determined. Lumbar curvature was monitored with a 3SPACE ISOTRAK[†] and was A/D converted at 20.5 Hz using customized software developed at the Occupational Biomechanics and Safety Laboratories at the University of Waterloo (Waterloo, Ontario, Canada). The ISOTRAK source, which produces an electromagnetic field, was mounted on the sacrum using a custom-built harness, and the sensor, which detects the rotational motion (three-directional cosines) with respect to the source, was mounted over the trunk midline at the T12-L1 spinal level.

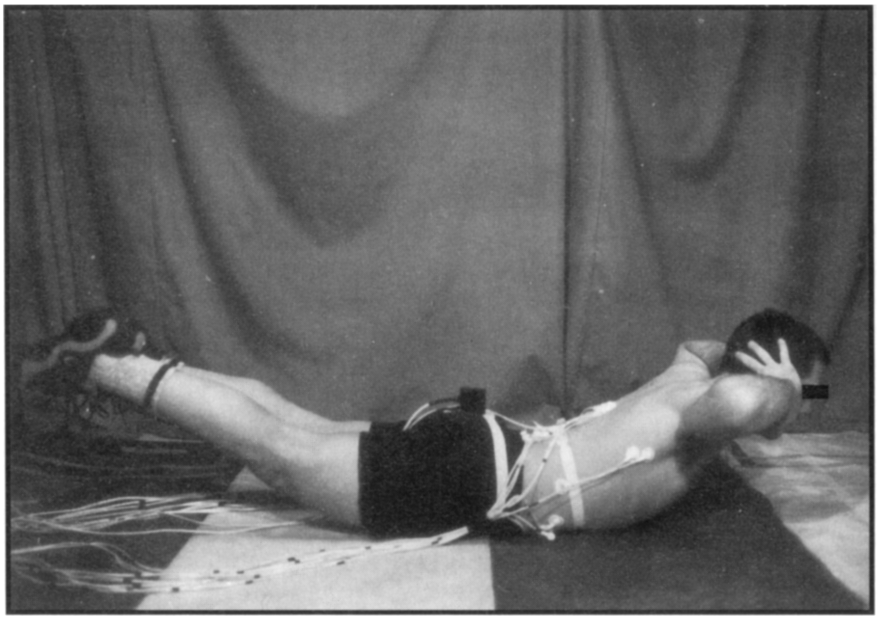

Figure 3.
Active trunk extension combined with leg extension was the fifth exercise. From a prone posture on the floor, subjects performed active trunk and leg extension (maximum comfortable) and returned to the prone position.

Synchronization of the ISOTRAK, EMG, and video signals was accomplished in the following way. At the beginning at the trial, the computer controlling the ISOTRAK sent a pulse through the A/D converter of a second computer (at 1,024 Hz), which initiated collection of the EMG signals. The same synchronized pulse activated a light-emitting diode in the field of view of the camera to mark the beginning of the trial. Later, selected samples from the A/D-converted data were matched with the appropriate video frame (at 30 Hz).

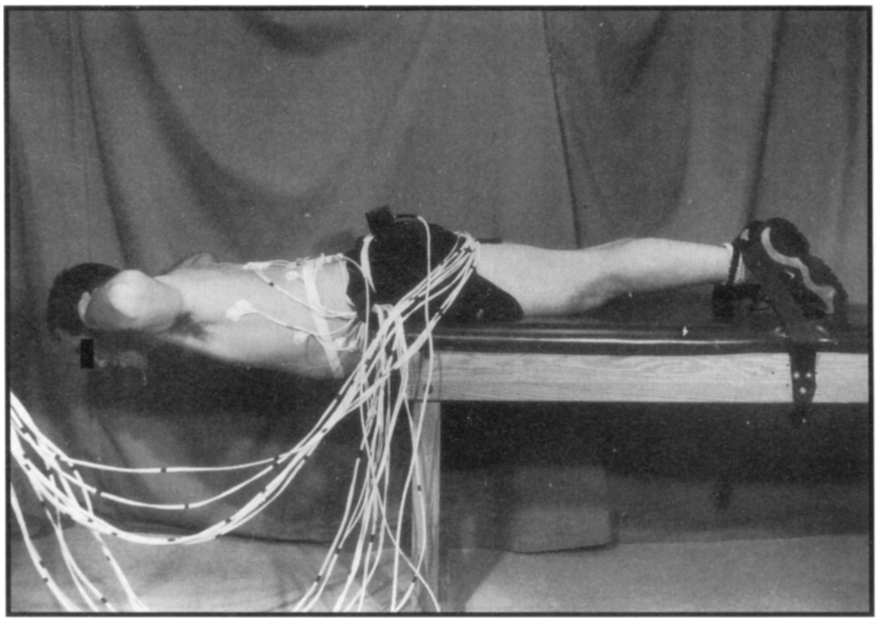

Figure 4.
Exercise 6 involved a large range of motion. The starting position was a fully flexed posture, followed by active extension until the trunk was horizontal to the ground, which corresponded to the peak loading posture (shown here).

Data Collection

Seven exercises were performed to determine the level of muscle activity and spinal loading. For the first four exercises, the subjects were positioned on their hands and knees. Exercises 1 and 2 consisted of a single-leg lift, performed by extending one leg out to the horizontal and returning it to the starting position. The right leg was lifted in exercise 1, and the left leg was lifted in exercise 2 (Fig. 1). Exercises 3 and 4 coupled the leg extensions of exercises 1 and 2 with the simultaneous raising of the contralateral arm to the horizontal before returning the extended leg and arm to the original position. Exercise 3 (Fig. 2) involved lifting the right leg and the left arm. Exercise 4 required lifting the left leg and the right arm. For exercises 5 and 6, the subjects were in a prone position. In exercise 5 (Fig. 3), the upper body and legs are raised simultaneously from the floor to a maximal comfortable elevation, with active spine extension, before being returned to the starting

[†] Polhemus, Division of Kaiser Aerospace Electronics Corp, PO Box 560, Colchester, VT 05446.

position. The trunk was cantilevered over a bench in exercise 6 (Fig. 4). A Velcro®‡ strap fastened proximally to the ankle was used to secure the lower limbs to the bench. The exercise started with the subjects in a fully flexed posture followed by trunk extension until the trunk was parallel with the ground. For each of these exercises, 10 seconds was allotted to perform one trial that consisted of three repetitions of the movement in succession. Subjects rested for at least 1 minute between trials. The seventh exercise was performed to allow a calibration of EMG activity to an external moment. Subjects stood with feet shoulder width apart and knees slightly bent. Holding a 10-kg weight in front of them, with arms hanging straight down, they positioned their trunk at an angle of 60 degrees from the vertical, maintaining a lordotic curvature of the spine. This posture was held for 10 seconds.

Three repetitions of all exercises were performed, for a total of 21 exercises per subject. The order of exercises was randomly assigned. For exercises 1 and 2, sagittal and transverse views were filmed on videotape. Sagittal views were filmed for exercises 3 through 7.

Data Reduction

The peak loading experienced by the subjects during the back exercises was the focus of this study. We therefore analyzed the postures representing this component of the exercises.

The ISOTRAK data, representing lumbar curvature, were used to determine the interval of maximum spinal extension. A window containing the point of maximal extension and 1 degree before and after it was selected. This interval also represented the greatest extensor moment, as identified from the videotape analysis. The intervals chosen for each repetition of an exercise were averaged to obtain a single value of spinal curvature. Spinal curvature was normalized to the curvature during relaxed upright standing (ie, 0°). Defining the posture of the lumbar spine during the normal standing position as 0 degrees (the reference point between flexion and extension) allows the amount of spine motion to be quantified within each individual and provides a common definition of the zero point for comparison between individuals.

Digital processing of the raw EMG signals included full-wave rectification followed by a Butterworth low-pass filter (2.5-Hz cutoff frequency) to produce a linear envelope. The filtered signals were then normalized to the maximum muscle activity that was elicited during the isometric contractions and synchronized to the ISOTRAK signal. The corresponding EMG windows for each repetition of an exercise were averaged for each of the 14 EMG channels.

A representative posture of maximum extension was identified using synchronized ISOTRAK data for all exercises. The corresponding videotaped data were digitized using a video capture system. Scaled joint coordinates were obtained with the use of customized software and were used to calculate extensor moments about the L4-5 joint for all exercises as well as twist moments for exercises 1 and 2, using typical two-dimensional rigid link-segment modeling.

A Brief Description of the Laboratory Modeling Approach

Individual tissue loads have been predicted from a laboratory technique and model developed over the past 14 years by McGill and colleagues.[13–15] The model is composed of two distinct parts. First, a rigid link-segment representation of the body was used to calculate reaction forces and moments about a joint in the low back (the L4-5 joint, as previously described by McGill and Norman[16]). Joint displacements were recorded on videotape at 30 Hz to reconstruct the joints and body segments. The first part of the model produces the reaction forces and corresponding moments about the axes of the low back (flexion and extension, axial twist). The second part of the anatomically detailed model allows the partitioning of the reaction moments obtained from the link-segment model into the substantial restorative moment components (supporting tissues) using an anatomically detailed, three-dimensional representation of the skeleton, muscles, ligaments, nonlinear elastic intervertebral disks, and so on. This part of the model was first described by McGill and Norman,[13] and full three-dimensional methods were described by McGill.[14] The most recent version of this part of the model, in which a total of 90 low back and torso muscles are represented, was described by Cholewicki and McGill.[15]

First, the passive tissue forces are predicted by assuming stress-strain or load-deformation relationships for the individual passive tissues. These passive forces are individualized for the differences in flexibility of each subject by scaling the stress-strain curves to the passive range of motion of the subject. The active range of motion was detected by electromagnetic instrumentation that monitors the relative lumbar angles three-dimensionally. Once the contributions of the passive tissues to moment restoration have been calculated, the remaining moment is then partitioned among the many laminae of muscle based on their EMG profile and their physiological cross-sectional area and modulated with known relationships for instantaneous muscle length and either shortening or lengthening velocity (force velocity described by Sutarno and McGill[17]). This method of using biological signals to solve the indeterminacy of multiple load-bearing tissues facilitates the assessment of

‡ Velcro USA Inc, 406 Brown Ave, Manchester, NH 03108.

Table.
Mean Activation Levels (±1 SD) of the 14 Electromyographic Channels for the 13 Subjects Expressed as a Percentage of Maximal Voluntary Contraction

Electromyographic Channel[a]	Extension						Calibration Posture
	Right Leg	Left Leg	Right Leg and Left Arm	Left Leg and Right Arm	Trunk and Legs	Trunk	
Right RA							
$\bar{X}$	3.3	2.7	4.0	3.5	4.7	3.1	1.4
SD	2.4	1.9	2.0	2.0	2.2	1.8	1.0
Right EO							
$\bar{X}$	8.4	4.9	16.2	5.2	4.3	3.7	1.0
SD	4.9	1.5	6.0	2.3	2.5	1.7	0.6
Right IO							
$\bar{X}$	12.0	8.2	15.6	12.0	12.1	12.7	1.9
SD	6.8	2.5	8.2	4.2	10.1	10.8	1.2
Right LD							
$\bar{X}$	8.1	5.8	12.0	12.5	11.2	6.5	5.9
SD	5.4	3.5	9.6	6.2	4.3	4.0	8.5
Right TES							
$\bar{X}$	5.7	13.7	11.5	46.8	66.1	45.4	21.0
SD	2.0	7.5	6.6	29.3	18.8	10.6	9.0
Right LES							
$\bar{X}$	19.7	11.7	28.4	19.4	59.2	57.8	21.3
SD	9.1	4.9	10.2	11.0	11.7	8.5	4.6
Right MF							
$\bar{X}$	21.9	10.8	31.5	16.1	51.9	47.5	16.4
SD	6.3	6.0	8.2	12.0	14.7	12.3	5.6
Left RA							
$\bar{X}$	4.3	3.6	4.4	4.2	6.5	3.7	2.2
SD	3.4	3.6	3.8	3.9	3.4	2.4	2.1
Left EO							
$\bar{X}$	5.4	9.0	6.2	15.9	6.3	5.2	1.8
SD	2.0	3.8	2.5	6.6	3.2	5.2	1.0
Left IO							
$\bar{X}$	16.0	11.3	22.6	15.2	11.0	12.5	1.6
SD	8.6	7.0	9.2	6.7	5.9	6.1	1.3
Left LD							
$\bar{X}$	4.5	5.0	10.7	6.2	9.2	5.1	6.1
SD	4.3	4.5	18.2	4.4	5.1	4.1	8.5
Left TES							
$\bar{X}$	15.0	4.5	42.9	10.5	63.6	41.6	21.2
SD	7.5	2.0	20.5	5.9	22.7	10.0	9.8
Left LES							
$\bar{X}$	11.3	16.8	19.5	25.5	56.8	57.0	23.3
SD	6.6	4.5	7.4	7.3	14.5	14.7	8.4
Left MF							
$\bar{X}$	11.9	22.3	16.6	33.8	57.3	53.3	18.7
SD	7.0	6.1	7.2	6.7	11.4	12.0	4.3

[a] Electromyographic channel: RA=rectus abdominis muscle, EO=external oblique muscle, IO=internal oblique muscle, LD=latissimus dorsi muscle, TES=thoracic erector spinae muscle, LES=lumbar erector spinae muscle, MF=multifidus muscle.

the many ways that we choose to support loads, an objective that we believe is necessary for evaluation of various tasks prescribed in exercise and rehabilitation programs.

Although the major asset of this biologically based approach is that muscle co-contraction is fully accounted for together with being sensitive to the differences in the way that individuals perform a movement, estimations of muscle force based, in part, on EMG signals are problematic because the force per muscle cross-sectional area must be assumed along with other variables that are known to affect force production. Furthermore, accurate anatomical detail is essential to satisfy the moment requirements about all three joint axes and about several joints simultaneously.

A major drawback of the EMG-based approach is the inaccessibility of the deeper torso muscles (eg, psoas, quadratus lumborum, three layers of the abdominal wall) to EMG analysis. In an attempt to address this drawback, McGill et al[18] used indwelling intramuscular

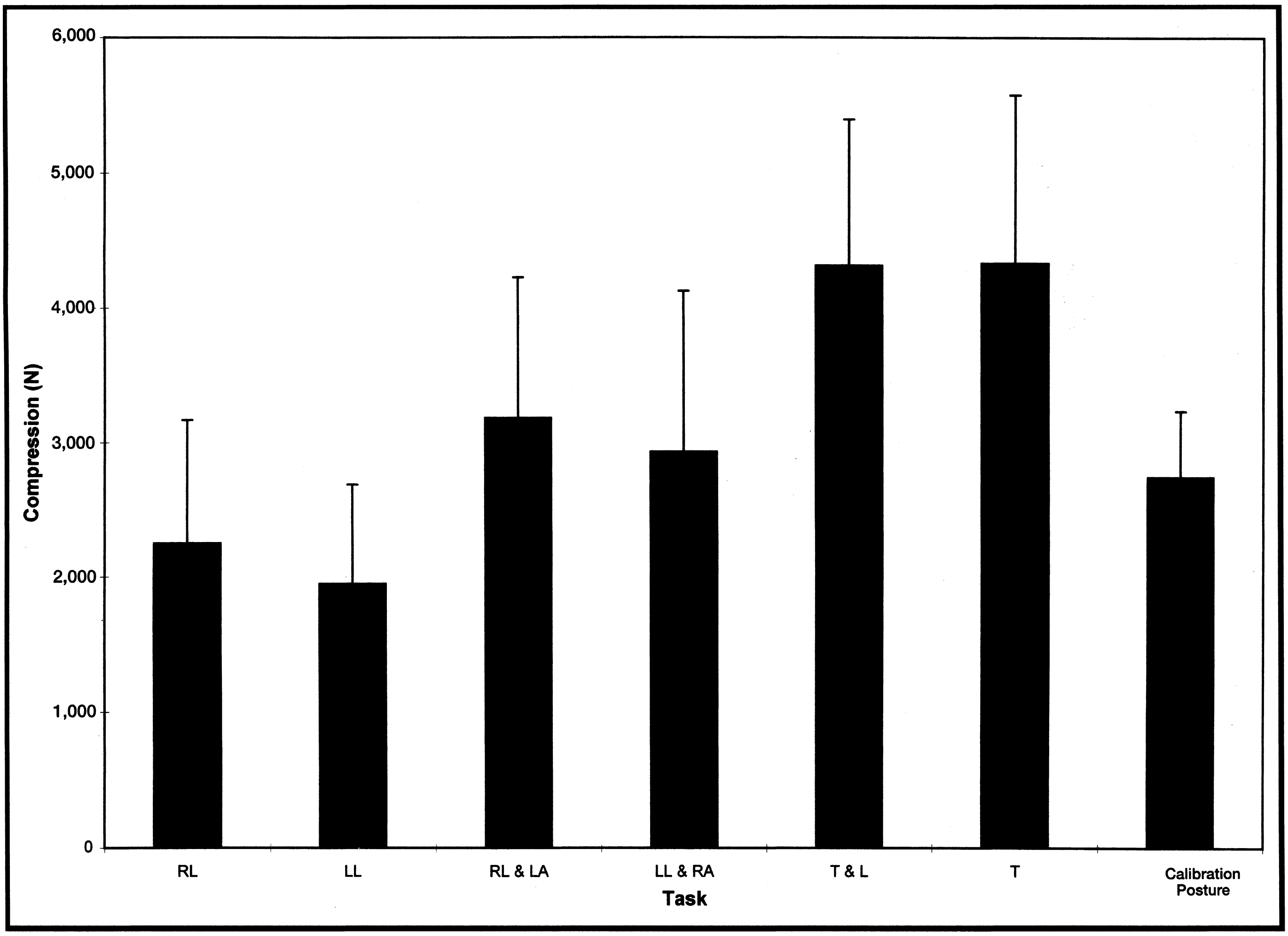

Figure 5.
Electromyographic model predictions of joint compression (mean and standard deviation) for all trials and across all subjects (N=13). RL=right leg extension, LL=left leg extension, RL & LA=right leg and left arm extension, LL & RA=left leg and right arm extension, T & L=trunk and leg extension, T=trunk extension.

electrodes with simultaneous stimulation of surface electrode sites to evaluate the possibility and validity of using surface activity profiles as surrogates to activate deeper muscles over a wide variety of tasks and exercises (eg, sit-ups, curl-ups, leg raises, push-ups, spine extensor tasks, lateral bending, twisting tasks). Prediction of the activity of these deeper muscles is possible from well-chosen surface electrodes within the criterion of 15% of maximal voluntary contraction (root mean square difference).[18]

One-way (dependent variable=task, α=.05) repeated-measures analyses of variance were performed on all 14 EMG channels, lumbar compression, and shear loading results. Tukey's *post hoc* multiple comparisons were used to examine tasks when a difference was found.

Results

Tasks involving active trunk extension against gravity produced the highest demands on the musculoskeletal system. The two trunk extension trials (trunk and leg extension, trunk extension) resulted in the highest extensor muscle activity (Table) and in the largest compressive joint forces (Fig. 5). Overall, the tasks involving the lowest joint load and muscle activity levels were the two single-leg extension tasks (right leg extension, left leg extension). Leg extension coupled with contralateral arm extension (right leg and left arm extension, left leg and right arm extension) increased the joint compression forces (1,000 N, $P<.001$) and upper erector spinae muscle activity levels (30%, $P<.0001$) compared with single-leg extension.

The joint compressive force showed an increase with increasing demand of the exercise when single-leg extension was compared with combined arm and leg extension (1,000 N, $P<.001$) and combined arm and leg extension was compared with trunk extension (1,200 N, $P<.001$). Due to the different loading of the tasks involving leg extension and those requiring trunk exten-

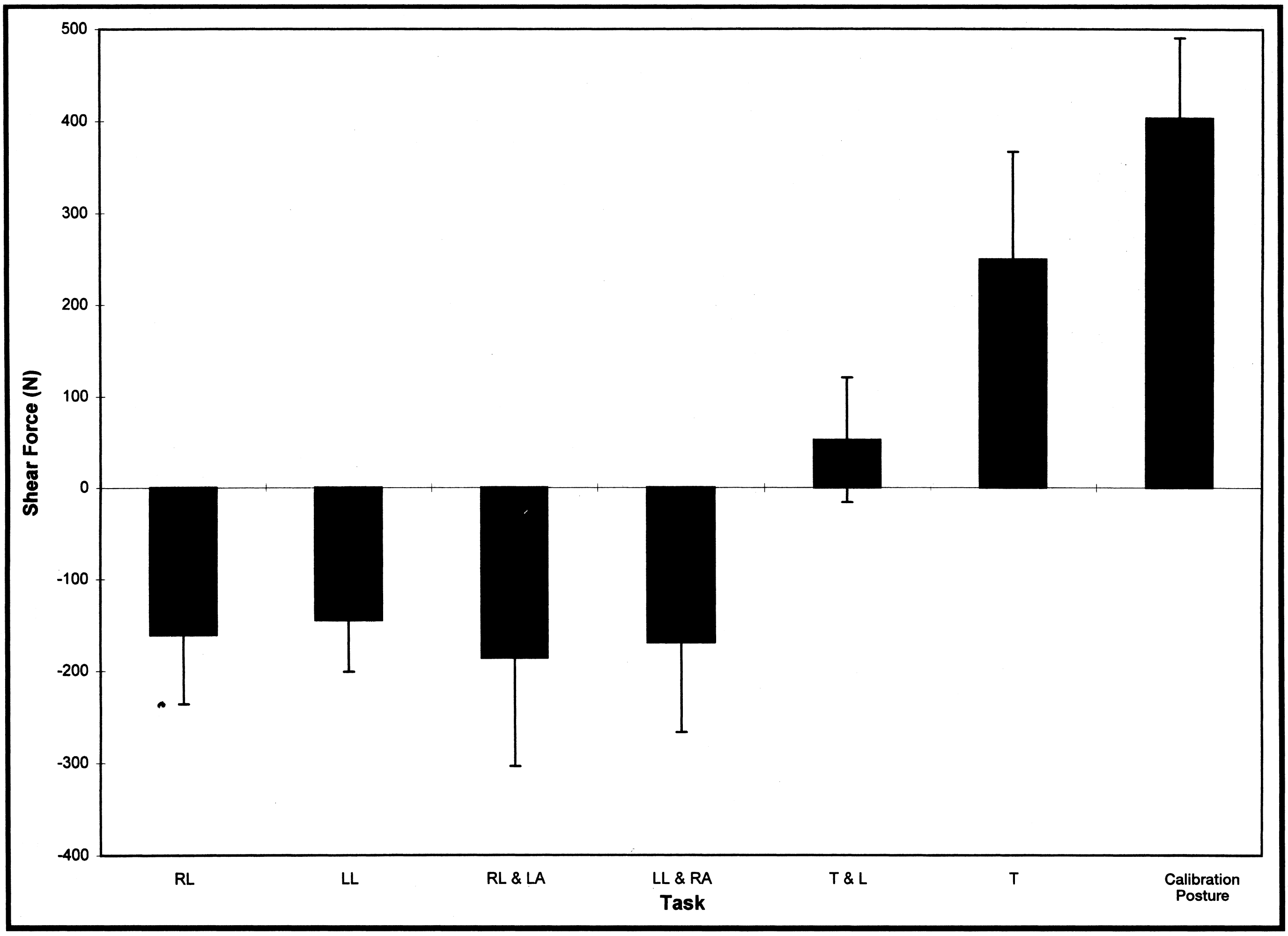

Figure 6.
Anteroposterior joint shear forces (mean and standard deviation) calculated by the electromyographic-driven model for all subjects (N=13). A positive shear value indicates a net anterior shear of the trunk with respect to the pelvis. See Fig. 5 caption for description of abbreviations.

sion (ie, upper-body versus lower-body support), the polarities of the anteroposterior shear forces were opposite (Fig. 6). The magnitude of the shear forces for all exercises, however, fell below that occurring in the 10-kg lift and were small compared with recently suggested in vitro tolerance levels.[19,20] Similarly, all lateral shear magnitudes were negligible (Fig. 7), primarily due to the symmetrical nature of the tasks involving active trunk extension (bilateral muscle activity) and offsetting muscle activity in the isometrically held trunk in leg extension. Although there were clear asymmetrical activity patterns for the tasks involving leg extension (ie, right erector spinae muscle activity with right leg extension), the contralateral abdominal muscles were activated to maintain a neutral pelvis and spine posture, in effect balancing the internal moments and lateral shear forces. The lumbar curvature at the instant of peak loading showed consistent low levels of spinal flexion across the four tasks involving leg extension (Fig. 8). The active trunk and leg extension task resulted in an extended spine posture. The trunk extension task peak load posture was chosen when the trunk was parallel to the floor, thereby artificially creating what appeared to be a neutral spine posture.

Activity of the abdominal muscles was low for all tasks. Both the rectus abdominis and internal oblique muscles were recruited bilaterally for all tasks. The external oblique muscle demonstrated increased activity on the same side as the active leg in all four leg extension tasks. Activity of the latissimus dorsi muscle remained at relatively low levels for all exercises, with the highest levels associated with arm extension. The thoracic erector spinae muscle demonstrated the opposite pattern to the external oblique muscle in the combined arm and leg extension tasks and to a lesser degree in the leg extension tasks. Increased levels of thoracic erector spinae muscle activity were associated with elevation of the ipsilateral arm. The three back extensor groups monitored (thoracic and lumbar erector spinae muscles and multifidus muscle) followed the same trend as the joint compressive force. The trunk extensor tasks required

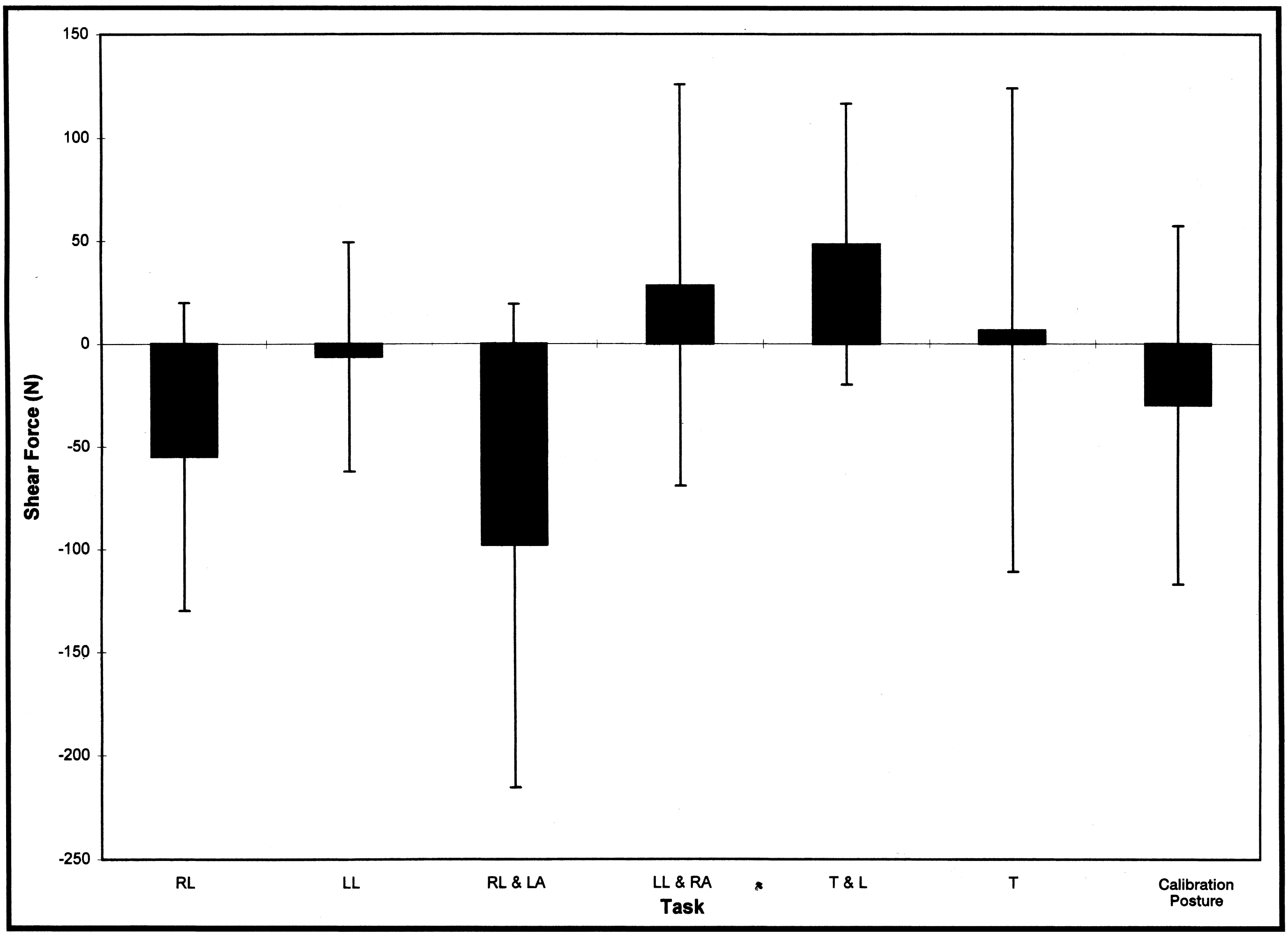

Figure 7.
Mediolateral joint shear forces (mean and standard deviation) calculated from the electromyographic-driven model for all subjects (N=13). A positive value indicates that the trunk is shearing to the subject's right with respect to the pelvis. See Fig. 5 caption for description of abbreviations.

the highest activity levels, whereas the leg extension tasks were the least demanding.

Discussion

Of the four typical exercises examined, only the single-leg extension tasks provided both low joint loading and muscular activity at a level, suggesting that these tasks would be a wise choice for persons beginning the muscle development part of a rehabilitation program. When compared with lifting a 10-kg mass (from approximately midthigh level), only the single-leg extension exercises resulted in less joint compression. The remaining three exercises (trunk extension, trunk and leg extension, leg and arm extension) generated high spinal loading and muscle activity levels. Very little co-contraction was present during any of the exercises. The hypothesis that some exercises would have higher levels of extensor activity with lower joint loading, therefore, was not demonstrated for our subjects without low back pain. Whether this finding would be true for persons with low back pain is not known. The modeling procedure that was used in our study showed that exercises, when performed with the low back close to neutral lordosis, reduce disk deformation, ligament loading, and ultimately spinal loading. Hyperlordosis (extension) has been shown to shift loading to the posterior elements, whereas hypolordosis (flexion) has been linked to a lower failure tolerance of the spine,[21] higher ligament loading,[22] and a higher risk of disk herniation.[23] The literature supports the importance of hip flexibility for successful low back rehabilitation. Lumbar flexibility remains questionable for some low back disorders, and in some cases spinal hypermobility has been associated with low back trouble.[24,25] Interestingly, Saal and Saal[26] noted success with carefully formulated exercises that emphasized muscle co-contraction with the spine in a neutral posture. The data that we report also show that the tasks involving leg extension preserve a more neutral lumbar posture and reduce spinal load because only one side of the extensors at a time dominates the contraction.

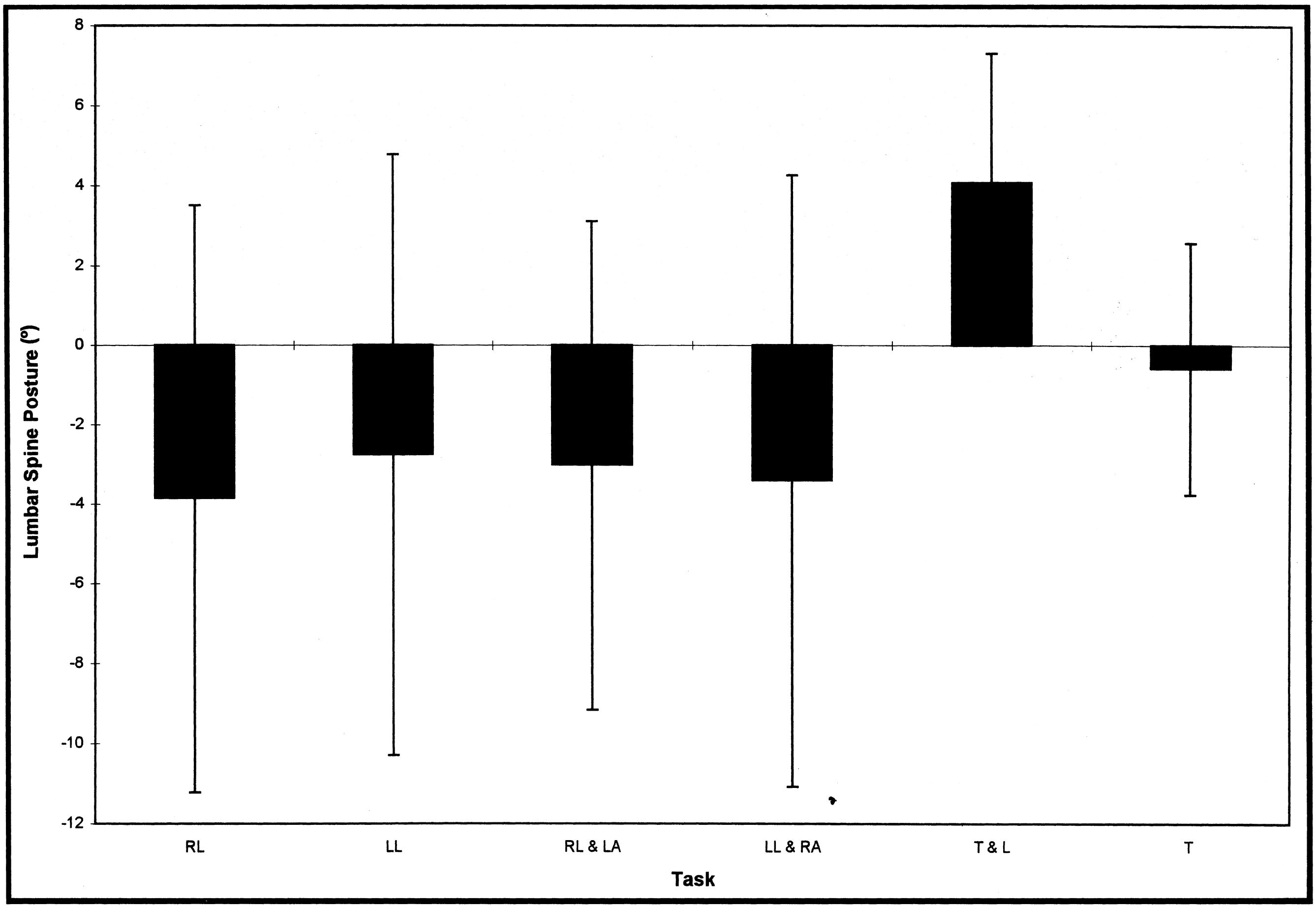

Figure 8.
Lumbar sagittal-plane spinal posture (mean and standard deviation) for all subjects (N=13) in the peak load position. A positive value indicates trunk (T-12 level) extension with respect to the sacrum; a negative value represents lumbar spine flexion. See Fig. 5 caption for description of abbreviations.

Only male subjects without low back pain were studied, and they are not representative of the patients who perform these exercises as a treatment for back pain. Our objective, however, was to quantify muscle activity and lumbar loading. The types of tasks studied presented a challenge from a modeling perspective because the subjects were positioned prone on the floor in some tasks, with contact forces distributed over their torso, making the external moment calculations more difficult. This difficulty was overcome by establishing a fixed relationship of maximum possible muscle stress (in newtons per square centimeter) for each subject. This relationship was established during the calibration task (exercise 7). Finally, although the tasks involved movement, measurements were taken only when the extreme positions were obtained, and this generated the largest external moments and levels of muscle activity and spinal loading. The tasks were performed smoothly and at a slow speed, thereby reducing inertial components at the initiation of each repetition.

Conclusion

The exercises examined provide a range of joint loading and muscle activity levels. The leg extension tasks could be suitable for the majority of patients who need increased endurance and strength enhancement. The increased demand of combining arm extension with leg extension suggests that this exercise constitutes an increased level of challenge. Although commonly used in rehabilitation protocols, the exercises involving trunk extension while lying prone on the floor (the prone press-up) require very high muscle activity levels and resulted in substantial joint loads, suggesting that their use is unwise.

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