# Low back loads over a variety of abdominal exercises: searching for the safest abdominal challenge

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## ABSTRACT

AXLER, C. T. and S. M. McGILL. Low back loads over a variety of abdominal exercises: searching for the safest abdominal challenge. *Med. Sci. Sports Exerc.*, Vol. 29, No. 6, pp. 804–810, 1997. Abdominal exercises are prescribed for both the prevention and treatment of low back injury. However, these exercises sometimes appear to have hazardous effects on the lumbar spine. The purpose of this study was to identify quantitatively abdominal exercises that optimize the challenge to the abdominal muscles (rectus abdominis, external oblique, internal oblique) but impose minimal load penalty to the lumbar spine. Nine volunteers performed 12 different abdominal exercises. For a given task the maximum abdominal muscle EMG value was divided by the maximum compression value, resulting in an abdominal challenge versus spinal compression cost index. In general, the partial curl-ups generated the highest muscle challenge-to-spine cost indices. However, those exercises that generated the best challenge-to-cost indices did not necessarily record the lowest compression levels along with the highest EMG activations. No single exercise was found that optimally trained all of the abdominal muscles while at the same time incurring minimal intervertebral joint loads. It was concluded that a variety of selected abdominal exercises are required to sufficiently challenge all of the abdominal muscles and that these exercises will differ to best meet the different training objectives of individuals.

LOW BACK, LUMBAR, ABDOMINAL EXERCISE, EMG

Abdominal exercises are prescribed for a variety of reasons, but mainly for rehabilitation of low back injury and as a component of fitness training programs (6,19). In the past, abdominal exercises have been recommended for their capacity to maximize muscle activity (3,21). However, some investigators have raised concern regarding the safety of abdominal exercise programs, with suspicion that tissue damage can occur (5,7,11,20), especially through compressive loading on the lumbar spine (16,18,20). Unfortunately, the level of risk of low back injury from performing various abdominal exercises, quantified by measures of tissue loading, has not yet been sufficiently examined (7). The purpose of this study was to identify quantitatively abdominal exercises that optimize the amount of abdominal muscle recruitment (or "challenge" to the abdominal muscles), with a simultaneous minimization of compressive load, or "penalty" to the lumbar spine.

The primary objective of this study was to identify safer and more effective exercises to train the abdominal musculature. Sub questions that were investigated included: do partial curl ups, sit-ups with bent legs, and leg raises decrease the compressive load on the spine as compared with straight leg sit-ups while maintaining the same level of muscle activation; do less conventional exercises, such as isometric torso flexion and twisting tasks, increase muscle activation but with no increase in spine load; does one abdominal exercise best activate all abdominal muscles simultaneously? In fact, there may not be one definitive exercise that optimizes the abdominal challenge with minimal low back loading. Interindividual differences in injury status and/or training goals may allow for a continuum of required muscle stress and acceptable loading of the low back. Exercises that may be harmful to some people because of facet, disc, or muscle injury may be advantageous to others. To accommodate for differences among individuals, we used a biologically-based modeling technique (that uses measures of 3D spine kinematics and multichannel EMG) to estimate low back tissue loads, including lumbar intervertebral joint forces, during a variety of tasks designed to challenge the abdominal muscles. In this way, the exercises could be rank ordered along a continuum from easiest to most difficult, coupled with an index for safety purposes. This would provide clinicians and trainers with information necessary to choose the most appropriate exercise for the individual at a given stage of the rehabilitation or training process.

## METHODS

**Subjects.** Nine men ((mean ± SD) age, 23 ± 4.8 yr; height, 1.78 ± 0.07 m; weight, 85.1 ± 19.0 kg) volun-

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TABLE 1. Description of exercises.

| Exercise | Description |
|---|---|
| A. Straight-leg sit-up (STRLSP) | Lying supine<br>Legs straight<br>Feet anchored under velcro foot strap<br>Arms positioned with fingers touching the cheeks<br>Torso raised to vertical position and lowered completely back down onto the mat |
| B. Bent-leg sit-up (BNTLSP) | Similar to straight-leg sit-up with one exception:<br>Knees bent to 90° |
| C. CSTF Curl-up (feet fixed) (CSTFFIX) | Similar to bent-leg sit-up with following exceptions:<br>Arms straight at sides of torso with hands flat on mat<br>Hands slid forward approximately 12 cm, effectively lifting head, shoulders, and upper torso off the bench |
| D. CSTF Curl-up (feet free) (CSTFFREE) | Similar to CSTF curl-up above with one exception:<br>Velcro foot strap not used to anchor feet |
| E. Quarter sit-up (QSP) | Similar to CSTF curl-up (feet free) with these exceptions:<br>Both hips and knees at 90° (effectively lifting the feet off the ground)<br>Arms positioned with fingers touching the cheeks |
| F. Straight-leg raise (STRLRS) | Lying supine<br>Hands under the lumbar region<br>Straight legs raised to 30° from horizontal |
| G. Bent-leg raise (BNTLRS) | Similar to straight-leg raise with these exceptions:<br>Knees bent at 90°<br>Bent legs raised until hips achieved 90° flexion |
| H. Dynamic cross-knee curl-up (XKNEEDY) | Similar to quarter sit-up with one exception:<br>Torso twisted to bring one elbow toward opposite knee (contact of elbow to knee NOT prescribed) |
| I. Static cross-knee curl-up (XKNEEST) | Similar to dynamic cross-knee curl-up above with the following exceptions:<br>Hand brought up to contact contralateral knee<br>Hand pushed against knee for resistance for 3 s |
| J. Hanging straight-leg raise (HANG) | Hanging with hands around chin-up bar<br>Straight legs lifted to horizontal position<br>Instruction given to avoid pelvic rotation |
| K. Hanging bent-leg raise (BNTHANG) | Similar to hanging straight-leg raise:<br>Knees bent to 90° |
| L. Isometric side support (ISOCSS) | Raise torso and legs off sit-up bench, supported by only right foot, right elbow, and right forearm |

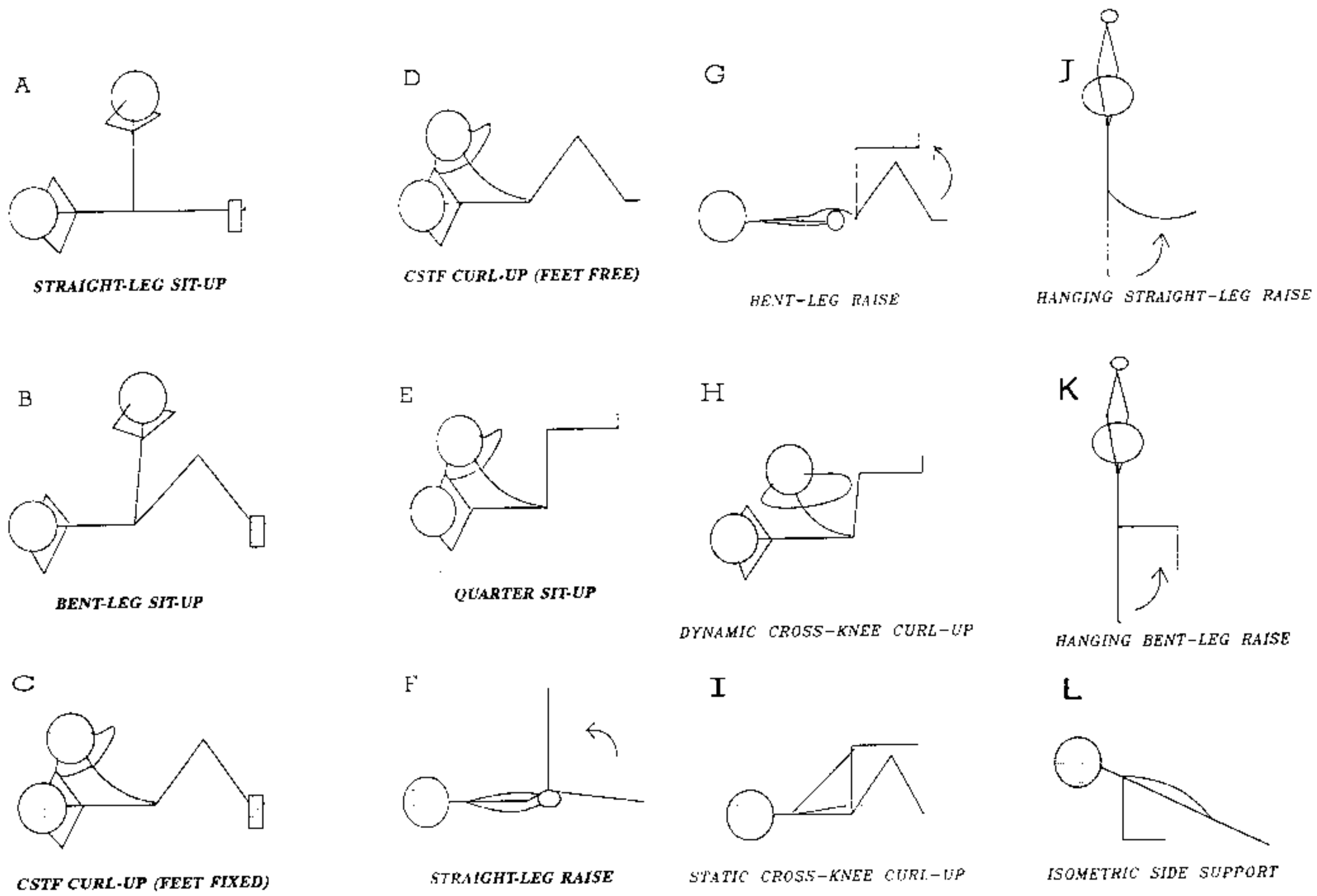
teered to participate in this study after signing an informed consent document. All were in good health and reported no incidence of acute or chronic low back injury or prolonged back pain prior to this experiment. Their history of abdominal exercising was neither investigated nor controlled. The informed consent document and test protocol was approved by the University of Waterloo Office of Human Research Ethics Committee.

**Tasks.** All nine volunteers were requested to perform 12 different abdominal exercises representing a wide range of different techniques. These exercises were presented in a random order. Participants received 4–6 min of rest between each exercise, during which equipment was readjusted and the next exercise was explained. Of the 12 exercises, 10 were dynamic and cyclical in nature, and two were isometric tasks (see Table 1 and also Fig. 1A-L).

Training sessions were provided to ensure that each participant understood the correct technique. For exercises A-H, five repetitions were recorded. Because data collected from the first or last repetition may have been clipped and therefore incomplete, analysis was performed on the middle three repetitions only. These exercises were performed in synchronization with a metronome at a rate of 25 repetitions per minute (0.417 Hz); consistent with the standards developed for the Canadian Standard Test of Fitness Partial Curl-up (CSTF Operations Manual (1)). Performing the exercises at this rate resulted in 12 s of activity for analysis. Performing straight- and bent-leg lifts while hanging from a chin-up bar was subjectively more physically demanding; therefore, only three repetitions of these exercises were performed in a 12-s period. The isometric tasks were both held in the position or positions of interest for 5 s each. Each participant was asked to return to a completely supine position on the sit-up bench between each cycle.

**Data collection.** All of the abdominal exercises, except for the hanging leg raises, were performed on a test bench, which had a 12-inch-longitudinal by 6-inch-lateral hole to accommodate the spine kinematics recording equipment. Despite this hole, the torso, hips, and buttocks were completely supported in a supine position, ensuring that the abdominal exercises could be performed in a similar manner if the participant were on a regular floor. The hanging leg raises were performed with the use of a chin-up bar braced 60 cm out from the wall. All exercises were performed on the same day.

EMG signals were recorded from the right and left sides of eight different muscles about the torso including the rectus femoris, providing EMG information from 16 electrode sites. Eight pairs of silver-silver chloride EMG surface electrodes were placed 3 cm apart, center to center, on the skin over the following muscles: upper rectus abdominis (3 cm lateral and 5 cm superior to the umbilicus), lower rectus abdominis (3 cm lateral and 5 cm inferior to the umbilicus), external oblique (approximately 15 cm lateral to the umbilicus), internal oblique (halfway between the anterior superior iliac spine of the pelvis and the midline, just superior to the inguinal ligament), rectus femoris (over the muscle belly just below the inguinal ligament), latissimus dorsi (lateral to T9 over the muscle belly), upper (thoracic) erector spinae (5 cm lateral to the T9 spinous process), and lower (lumbar) erector spinae (3 cm lateral to the L3 spinous process). EMG signals were A/D converted via a 12-bit, 16-channel A/D converter at 1024 Hz, full-wave rectified and low pass filtered (Butterworth) at 2.5 Hz. This output was then normalized to each volunteer's maximal myoelectric activity


A STRAIGHT-LEG SIT-UP

B BENT-LEG SIT-UP

C CSTF CURL-UP (FEET FIXED)

D CSTF CURL-UP (FEET FREE)

E QUARTER SIT-UP

F STRAIGHT-LEG RAISE

G BENT-LEG RAISE

H DYNAMIC CROSS-KNEE CURL-UP

I STATIC CROSS-KNEE CURL-UP

J HANGING STRAIGHT-LEG RAISE

K HANGING BENT-LEG RAISE

L ISOMETRIC SIDE SUPPORT

**Figure 1—Diagrams of the abdominal exercises.**

(or maximal voluntary contraction, MVC) at each muscle site (obtained through a series of maximal exertion tasks (9) and expressed as a percentage of this value).

Lumbar spine kinematics were recorded using the 3-SPACE ISOTRAK II tri-axial displacement monitor. Its source was positioned over the sacrum and secured with straps around the torso and between the legs. The sensor was located over the T12 spinous process and also strapped around the torso. More detailed information regarding this instrumentation can be found in McGill et al. (15).

A video camera recorded the external segment kinematics in the planes of movement of the volunteers during the performance of each abdominal exercise. Light-reflective markers were placed on the right metatarsal, ankle, knee, hip, hand, wrist, elbow, shoulder, L4/L5 joint, ear canal, and C7/T1 joint. These markers were used as guides for digitizing the joint centers after the actual data collection period, using the Peak Performance motion analysis system, edition 5.0(Peak Performance Technologies, Inc., Englewood, CO). Digitized coordinates were sampled at 15 Hz. These data were used to construct a 3-dimensional link-segment model of the body to determine the external moment about the L4/L5 joint.

**Data reduction.** A summary of the model used to estimate the compression and shear at the L4/L5 joint is provided here. For a more comprehensive description of the model, readers are directed to McGill and Norman (12), with improvements documented in McGill (10) and Cholewicki and McGill (2).

Essentially, the model had two component parts, the LINK SEGMENT model and the SPINAL model. The LINK SEGMENT model uses digitized body joint coordinates from the video to determine the three orthogonal dynamic reaction moments acting about the L4/L5 intervertebral joint. Several assumptions were made to estimate the lumbar reaction moments. During those tasks in which the upper body was in contact with the bench, moments were estimated in the following way: for curl-ups, the moment was calculated about T6 as the arms, head, and upper torso were supported against gravity; for leg raises and hanging exercises, the moments were calculated about the hip joints. The EMG modulating and calibration coefficients were determined during those valid tasks in which no external forces were applied to the upper body and used for those tasks where forces were applied to the upper torso, for example, curl-ups. The anatomically detailed SPINAL MODEL partitioned these three moments into moment supporting tissues (approximately 60 muscles, 13 ligaments at the joint, nonlinear elastic disc, deformed gut, and passive tissues) using lumbar kinematic information from the 3-SPACE

ISOTRAK and the EMG signals. Passive tissues' stress-strain relationships were determined from calibration postures and thus were a function of lumbar geometry. Muscle forces were estimated by knowledge of their physiologic cross-sectional area, neural activation, stress, instantaneous length, and velocity. In this way the instantaneous force-time histories were predicted for major supporting tissues of the torso which were applied to skeletal components to estimate joint compression and shear loading.

An important consideration for this experiment was the psoas muscle which is not accessible using only surface electrodes. McGill et al. (14) recently examined the validity of using surface EMG surrogates to represent psoas activity and determined that rectus femoris surface EMG best represented indwelling psoas EMG during bent-knee and straight-leg sit-ups (RMS difference of less than 12% of % MVC) and leg raises (RMS difference less than 14% of % MVC). Once the low back compression and shear force values had been calculated over the time history of each exercise, the normalized EMG and compression records of three repetitions of each exercise were ensemble averaged from 0 to 100% of the task cycle. The maximum EMG value from a given task was divided by the corresponding maximum compression value, resulting in an abdominal challenge versus spinal compression cost index for each exercise. These mean indices were calculated for each of the four abdominal muscles directly monitored; upper and lower rectus abdominis, external, and internal oblique. The 12 exercises were then ranked based on their abdominal activity versus spinal load cost indices for each muscle group.

In addition, these activities were also ranked on their maximum EMG and maximum compression values alone. A one-way ANOVA was performed on the compression values from each task, and a two-way ANOVA was performed on the maximum EMG levels from each task for each of the four abdominal muscle sites, significance level $P \leq 0.05$. Tukey's HSD *post hoc* test was used to identify the origin of any significant differences.

## RESULTS

The peak flexion moments (except for side support where the moment was about the lateral bend axis) for the low back (Table 2) demonstrated the relative demand of each task; specifically, bent leg sit-ups produced the highest moment and curl-ups the least. Contrary to popular belief, no difference in the lumbar spine compression was observed between sit-ups performed with the legs bent versus straight (see Fig. 2). Compression arising from subtle shifts in muscle activation and in the force-length curve of the psoas muscle during the two types of sit-ups demonstrated no significant difference in psoas forces (see Table 3).

TABLE 2. Peak flexion moments (except for isometric side support where the moment is lateral bend) about L4/L5, demonstrates the relative demand of each task.

| Task | Moment (N.M.) | |
|---|---|---|
| | x | SD |
| Straight leg situp | 148 | 27 |
| Bent leg situp | 154 | 30 |
| CSTF curlup (feet fixed) | 92 | 19 |
| CSTF curlup (feet free) | 81 | 11 |
| Quarter situp | 114 | 27 |
| Straight leg raise | 102 | 24 |
| Bent leg raise | 82 | 36 |
| Dynamic cross-knee curlup | 112 | 22 |
| Static cross-knee curlup | 133 | 25 |
| Hanging straight leg raise | 107 | 17 |
| Hanging bent leg raise | 84 | 17 |
| Isometric side support | 72 | 13 |

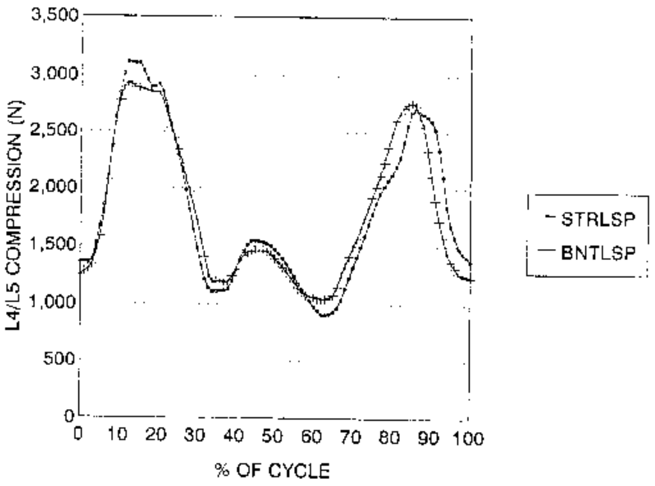


**Figure 2—Averaged compression values during the straight-leg sit-up (STRLSP) and the bent-leg sit-up (BNTLSP).**

The hanging straight-leg raise (HANG) and the CSTF curl-ups had the highest (optimal) challenge-to-compressive-cost indices from the upper and lower rectus abdominis electrode sites (see Fig. 3). The full sit-ups ranked near the middle on the scale, along with the quarter sit-up (QSP) and the dynamic cross-knee curl-up (XKNEEDY). The supine leg raises generally produced the lowest indices for all of the abdominal muscles.

The oblique challenge-to-compression indices showed some systematic differences from the rectus abdominis sites (Fig. 4). The asymmetrical nature of the twisting curl-ups and the isometric side support (ISOCSS) increased the challenge to the obliques for a given level of L4/L5 spinal compression relative to the other tasks. Conversely, exercises that required only a partial curl-up of the torso (CSTFFIX, CSTFFREE, and QSP) produced the opposite effect.

Abdominal exercises achieved high challenge-to-compressive indices through either maximization of abdominal activity or thorough minimization of L4/L5 compression. No exercise successfully accomplished both of these goals simultaneously. The straight-leg sit-up (STRLSP) and the static cross-knee curl-up (XKNEEST) produced a compressive penalty significantly higher than

TABLE 3. The forces attributed to the abdominal and psoas muscle fascicles by the model during the torso-lifting portion of the straight-leg sit-up and the bent-leg sit-up (analysis of the same subject).

| Muscle | Straight-Leg Sit-Up | | | | Bent-Leg Sit-Up | | | |
|---|---|---|---|---|---|---|---|---|
| | Force (*N*) | Compression (*N*) | A-P Shear (*N*) | Lat. Shear (*N*) | Force (*N*) | Compression (*N*) | A-P Shear (*N*) | Lat. Shear (*N*) |
| R Rectus abdominus | 199 | 195 | 18 | 25 | 179 | 176 | 29 | −25 |
| L Rectus abdominus | 212 | 208 | 19 | 27 | 188 | 185 | 31 | 26 |
| R External oblique I | 69 | 62 | 26 | 3 | 82 | 75 | 34 | 4 |
| L External oblique I | 42 | 38 | 16 | −2 | 56 | 52 | 24 | −2 |
| R External oblique II | 289 | 227 | 136 | −99 | 331 | 252 | 182 | −121 |
| L External oblique II | 136 | 106 | 64 | 47 | 191 | 145 | 105 | 70 |
| R Internal oblique I | 95 | 84 | −48 | 10 | 101 | 86 | −51 | 11 |
| L Internal oblique I | 53 | 47 | −27 | −5 | 49 | 41 | −24 | −5 |
| R Internal oblique II | 201 | 155 | −29 | 126 | 230 | 166 | −45 | 152 |
| L Internal oblique II | 99 | 77 | −14 | −62 | 98 | 71 | −19 | −65 |
| R Psoas (L1) | 61 | 58 | 21 | 13 | 70 | 66 | 24 | 15 |
| L Psoas (L1) | 38 | 36 | 13 | 8 | 39 | 37 | 13 | −8 |
| R Psoas (L2) | 62 | 58 | 21 | 15 | 70 | 66 | 24 | 17 |
| L Psoas (L2) | 39 | 36 | 13 | −9 | 39 | 37 | 13 | −9 |
| R Psoas (L3) | 62 | 58 | 21 | 17 | 71 | 66 | 24 | 20 |
| L Psoas (L3) | 39 | 36 | 13 | −11 | 39 | 37 | 13 | −11 |
| R Psoas (L4) | 62 | 59 | 21 | 20 | 71 | 66 | 24 | 22 |
| L Psoas (L4) | 39 | 37 | 13 | −12 | 39 | 37 | 13 | −12 |

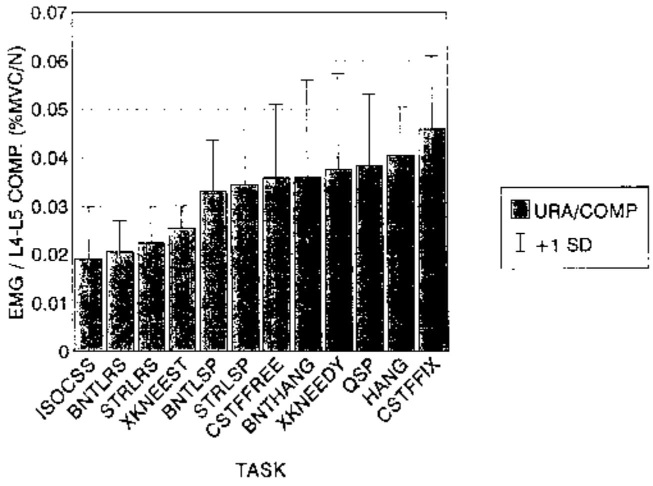


**Figure 3—Exercise challenge-to-cost indices from the upper rectus abdominis.**

the supine bent-leg raise (BNTLRS) ($P < 0.01$) and both CSTF partial curl-ups ($P < 0.05$) (see Fig. 5). The bent-leg sit-up (BNTLSP) also recorded significantly higher compression than the supine bent-leg raise ($P < 0.01$). In general, the full sit-ups generated the highest compressive forces, followed closely by the cross-knee curl-ups and the hanging leg raises.

For all four of the abdominal muscle sites, the supine bent-leg raise produced EMG intensities that were significantly lower than the hanging straight-leg raise (HANG) ($P < 0.01$) and the full sit-ups ($P < 0.05$). The supine bent-leg raise was also significantly less challenging to the upper rectus abdominis than the hanging bent-leg raise (BNTHANG), the sit-ups ($P < 0.01$), and the dynamic cross-knee curl-up (XKNEEDY) ($P < 0.05$) (see Fig. 6), as well as less challenging to the obliques than the static cross-knee curl-up ($P < 0.05$) (see Fig. 7). For the external oblique, the CSTF curl-up with the feet free (CSTFFREE) was also significantly less challenging than the hanging straight-leg raise ($P < 0.01$) (see Fig. 7). In general, the hanging straight-leg raise elicited the highest maximal activity from all of the abdominals, and the bent-leg raise produced the lowest. The asymmetrical exercises (XKNEEDY, XKNEEST, ISOCSS) provided greater challenge to the obliques than the rectus abdominis relative to the other tasks (see Figs. 6 and 7).

## DISCUSSION

With respect to our questions, performing sit-ups with bent knees did not significantly reduce lumbar spine compression (Fig. 5). This appears to agree with the recent intramuscular myoelectric work of Juker et al. (8) who monitored psoas and the deeper layers of the abdominal wall. Sit-ups with feet unanchored, legs elevated, or twists of the torso do not significantly increase the level of abdominal muscle activity (Fig. 6). The less conventional exercises that were examined (i.e., hanging

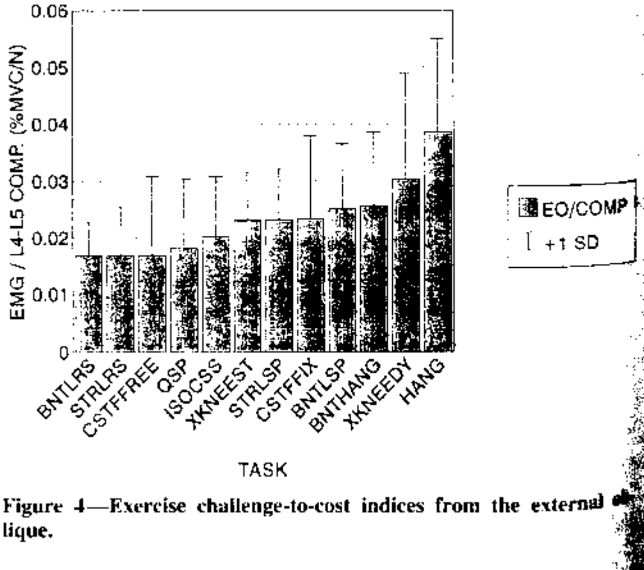


**Figure 4—Exercise challenge-to-cost indices from the external oblique.**

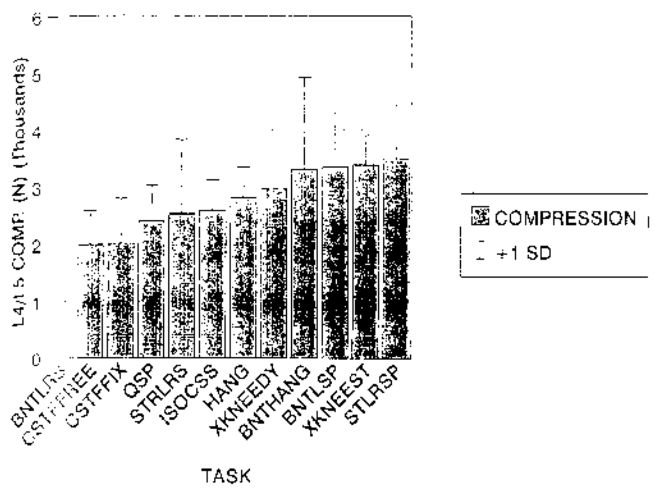


**Figure 5—Maximum compression values of each task, averaged across subjects.**

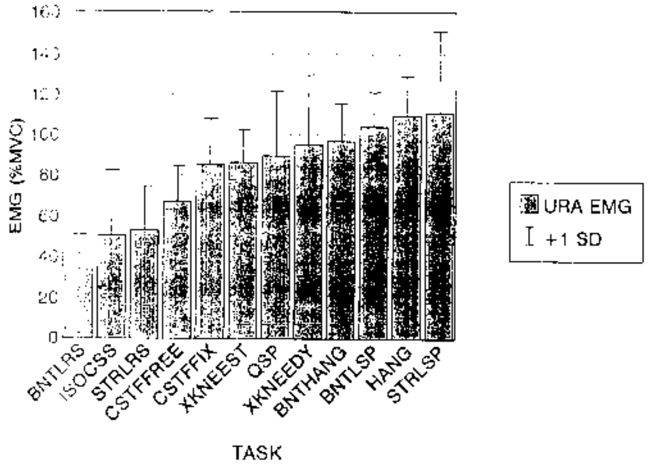


**Figure 6—Maximum upper rectus abdominis EMG intensity from each task, averaged across subjects.**

leg raises, isometric side support) would be suited only for specific populations, either because they required considerable strength to perform or because they were very specific in which abdominal muscle(s) they recruited. Furthermore, no single exercise best recruited all of the abdominal muscles simultaneously (see Figs. 6 and 7). The different functions of the obliques and the rectus abdominis make it difficult to accomplish this objective. Simple straight-leg sit-ups provide a good challenge for the rectus abdominis (see Fig. 6), but not for the external oblique (see Fig. 7). Asymmetrical exercises such as the isometric side support (ISOCSS) concentrate on oblique activity, but rate very poorly with the rectus abdominis (see Fig. 6). It would therefore appear that different abdominal exercises are best suited to different individuals. For the injured, exercises with high challenge-to-compression indices may still produce dangerously high levels of L4/L5 compression. The opposite would be true for strong and healthy individuals, who may seek maximal abdominal challenges, with little concern for lumbar spine stresses. Of the abdominal exercise variations to the straight-leg sit-up that were examined, only curl-ups effectively provide lower compressive loads for a given level of muscle challenge (5). Given these findings, abdominal exercises recommended for different groups of people are provided in Figure 8. The data in this table are presented in a three-dimensional format. In the first (vertical) plane, exercises were recommended/not recommended based on their challenge-to-compressive-cost indices. Along the second (horizontal) plane, the challenge-to-compressive-cost index was optimized through different means. At one end, the straight-leg sit-up maximized abdominal challenge, while at the other end the CSTF curl-ups minimized the compressive penalty. Along the third continuum which runs out of the figure, the isometric side support (ISOCSS) emphasized oblique activity as compared with the rectus abdominis, and the quarter sit-up (QSP) showed the opposite effect. Low back pain patients and athletes could orient themselves along the axis that best suits their individual exercise specifications.

The conclusions of this study are limited because all our participants were relatively physically fit. Further investigations should include people with health concerns because of age, injury, weight, etc. Also, only the maximal EMG levels during the exercises were evaluated without consideration for the duration of any muscular contraction. This may have penalized exercises which produced lower-level contractions for an extended period of time (such as the isometric side support) as opposed to periodic bursts of high level activity with periods of inactivity. Finally, Godfrey et al. (4) highlighted the important effect of the rate of performance on the muscle recruitment during an abdominal exercise. Performing exercises at a faster rate will generate higher accelerations requiring higher muscle forces. In this study the rate of repetition was controlled, not the angular acceleration of the torso. Those exercises that required a larger range

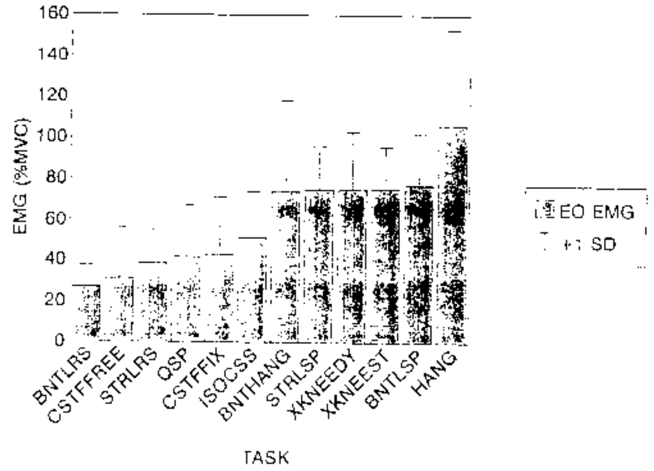


**Figure 7—Maximum external oblique EMG intensity from each task, averaged across subjects.**

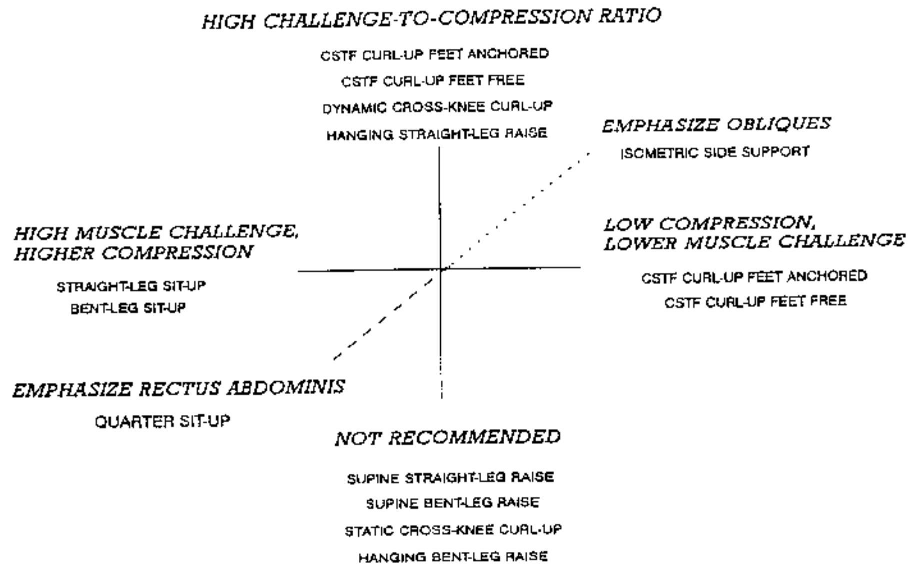


**Figure 8—Exercises recommended for specific purposes.**

of motion within a cycle would also require greater acceleration of body segments, and the muscular load required from these exercises would be artificially higher in relation to those other activities with lesser ranges of motion.

It is not possible to recommend universally those abdominal exercises with the highest abdominal challenge-to-compressive cost indices. Several exercises are required to train all the muscles of the abdominals, and the abdominal exercises best suited for an individual depend on a number of variables such as fitness level, training goals, history of previous spinal injury, and any other factors specific to the individual. One exercise not often performed but that appears to have merit is the horizontal side support because it challenges the lateral obliques without high lumbar compressive loading. In addition, this exercise produces high activation levels in quadratus lumborum which appears to be a significant stabilizer of the spine (13). This work represents an attempt to identify the safest abdominal exercise using quantitative measures. Given the time histories of tissue loading, the clinician may better select the most appropriate exercise for an individual to protect a specific low back injury or to train a specific abdominal muscle.

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