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Lower back muscle forces in pushing and pulling

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In the investigation of lower back stress, the muscle forces of the erector spinae and the rectus abdominis are often calculated using the two-dimensional biomechanical model. These muscle forces are used to estimate the compressive forces at L5/S1 disc. This paper presents a study of the muscle forces predicted by a two-dimensional biomechanical model during pushing and pulling and myoelectric activity from the corresponding muscles. The goal was to investigate whether a simple two muscle torso model would reasonably estimate the muscle actions in pushing and pulling tasks. Six subjects participated in the experiment. EMG (rms) value was used as an indicator of muscle forces. The results show high correlation between the predicted muscle forces and the measured root-mean-square EMG values in trunk pushing and pulling ($r^2 = 0{\cdot}93$) and hand pushing and pulling ($r^2 = 0{\cdot}96$) in an erect posture with hips braced but low in hand pushing and pulling using a free posture ($r^2 = 0{\cdot}37$).

1. Introduction

In the investigation of lower back stress, the muscle forces of the erector spinae and the rectus abdominis are often calculated using the two-dimensional biomechanical model. These muscle forces are used to estimate the compressive forces at L5/S1 disc. Most of such work has been done for isometric lifting. Little has been done in prediction of these forces for pushing and pulling. In most cases, a biomechanical model for lifting has been used to estimate the lower back stress in pushing and pulling even though lifting has different characteristics to pushing and pulling (e.g. foot positions and posture).

Several researchers (Ayoub and McDaniel 1974, Chaffin *et al.* 1983, Gaughran and Dempster 1956, Kroemer 1974, Snook *et al.* 1969) have studied free standing pushing and pulling. Their studies were concerned mostly with the maximum pushing and/or pulling force, but have not evaluated lower back stresses or torso muscle actions.

Therefore, it is deemed necessary to investigate whether a simple two muscle torso model would reasonably estimate the muscle actions in pushing and pulling tasks.

Based on previous research (Chapman and Troup 1969, Lee 1982, Shultz *et al.* 1982, 1985), it was concluded that EMG amplitudes are reasonably proportional to the corresponding muscle forces with submaximal tension. Therefore, EMG measure (rms value) was used as an indicator of muscle forces (Agarwal 1982, Chaffin and Andersson 1984, Schultz *et al.* 1982, 1985).

2. Model description

The model used in this research for prediction of lower back muscle forces is basically the same as the one which has been used by several researchers (Anderson and Chaffin 1984, Chaffin 1972, Park and Chaffin 1974). It is a sagittal plane model and assumes that all external hand forces acting on the body do so at the centre of the grip of hands. The human body is assumed to be made up of 11 solid links (hand, lower arm, upper arm, upper trunk and neck, lower trunk, right and left upper leg, right and left lower leg, right and left foot). The mass of each link has been assumed to be proportional to the total body mass as indicated by the distribution from Dempster *et al.* (1964).

The rectus abdominis muscle force component (figure 1) is added to Chaffin's torso model (Chaffin 1972) as suggested by Anderson *et al.* (1980). The revision is described below. The moment at L5/S1 disc is derived from the moment equilibrium equation at the L5/S1 disc using the following equations (1) and (2):

$$M(\mathrm{L5/S1}) = (F(\mathrm{rec}) \cdot A) - (F(\mathrm{erc}) \cdot B) + M(\mathrm{abd}) \tag{1}$$

$$M(\mathrm{res}) = M(\mathrm{L5/S1}) - M(\mathrm{abd}) \tag{2}$$

where:

$M(\mathrm{L5/S1})$ = moment at L5/S1 disc
$M(\mathrm{abd})$ = moment at L5/S1 disc due to abdominal pressure
$M(\mathrm{res})$ = moment at L5/S1 disc after moment due to abdominal pressure is subtracted
$F(\mathrm{rec})$ = rectus abdominis muscle force
0 if $M(\mathrm{res}) > 0$ in pulling or $F(\mathrm{rec})$ otherwise
$F(\mathrm{erc})$ = erector spinae muscle force
0 if $M(\mathrm{res}) < 0$ in pulling or $F(\mathrm{erc})$ otherwise
A = moment arm of rectus abdominis muscle force to L5/S1 disc
B = moment arm of erector spinae muscle force to L5/S1 disc.

The solution assumes that only one muscle at a time is active to stabilize the torso (i.e., no antagonism exists). This assumption is necessary to evoke a simple static equilibrium solution. Then the compressive force is derived from the following force equilibrium equation (3) and equations (1) and (2):

$$F(\mathrm{comp}) = F(\mathrm{ex}) + F(\mathrm{erc}) + F(\mathrm{rec}) - F(\mathrm{abd}) \tag{3}$$

where:

$F(\mathrm{ex})$ = force by upper body weight and hand force normal to L5/S1 disc
$F(\mathrm{comp})$ = compressive force at L5/S1 disc.

This model requires the body weight, positions of the joints of the body, and forces exerted on the handle (hand forces) as inputs. It then allows computation of the reactive forces and moments at joints, the erector spinae and rectus abdominis muscle forces,

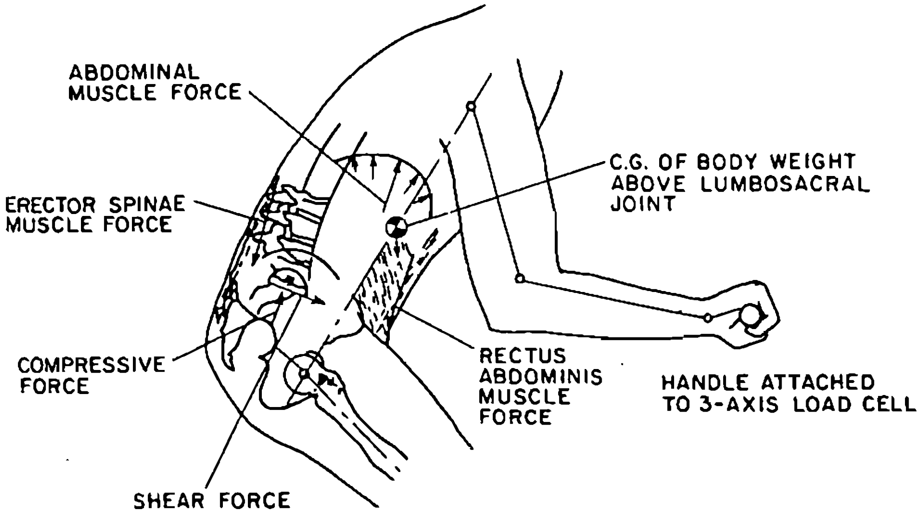

Figure 1. Free body diagram of lower back forces (Adapted and revised from Chaffin and Andersson 1984).

and the compressive forces at the L5/S1 disc as outputs. The abdominal pressure [*M*(abd)] and the resulting abdominal muscle force [*F*(abd)] were obtained using the method suggested by Chaffin (1972).

3. Method

The effectiveness of the model was tested by comparing the predicted muscle forces with EMG (rms) values of the rectus abdominis and erector spinae muscle measured during the experiment (figure 2). Three different series of pushing and pulling experiments were performed: trunk pushing and pulling, and hand pushing and pulling in an erect posture with the hips braced and hand pushing and pulling in a free posture at three different handle heights. To obtain the data of each joint position of a subject, the vertical and horizontal positions of the wrist, elbow, shoulder, L5/S1 disc, hip, knees and angles were photographed during each cycle. Hand forces (horizontal and vertical) were measured by the triaxial load cell which was connected to the handle of the pushing and pulling tester. The signals were captured at the sampling rate of 100 Hz and recorded in HP-2100 mini computer. A mandatory 5 min rest period was given between each test in all three experiments.

3.1. *Isometric trunk pushing and pulling*

In this experiment, EMG (rms) values were measured continuously while the subjects increased their force up to 100% maximum voluntary capacity (MVC) pushing and pulling force for 4 s in erect standing positions. The force was applied on a strap around the upper trunk (figure 3). A subject's thighs and hips were strapped for support. This experiment was repeated five times for pushing and pulling.

3.2. *Isometric hand pushing and pulling in standing erect posture*

In this experiment (figure 4), the subjects pushed or pulled on a static handle which was set at his/her shoulder height with the thighs and hips braced. Other aspects of the experimental design and method were identical to above experiment.

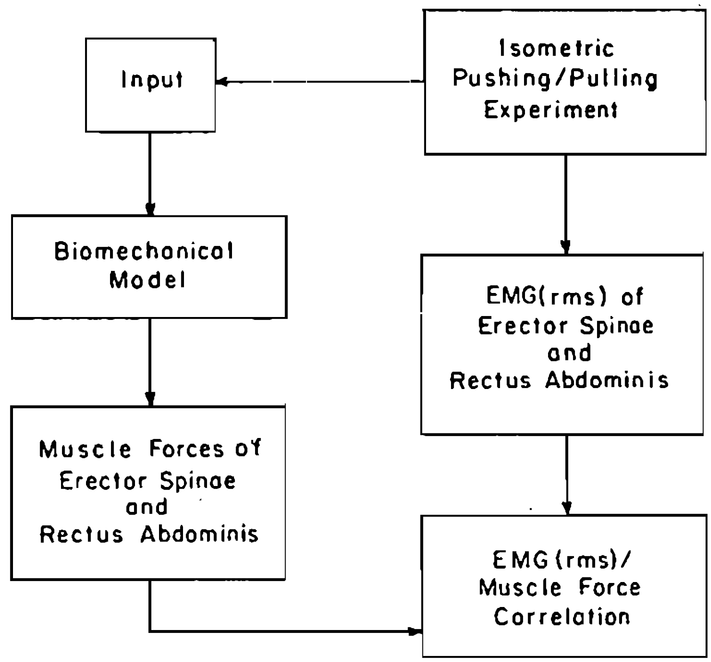

Figure 2. The steps in muscle force comparison with EMG (rms).

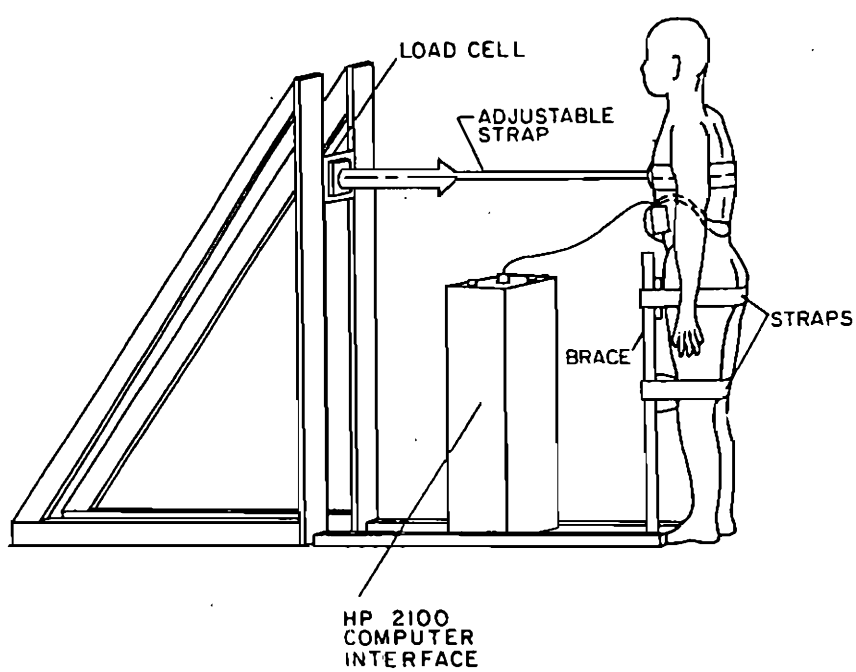

Figure 3. Isometric trunk pulling.

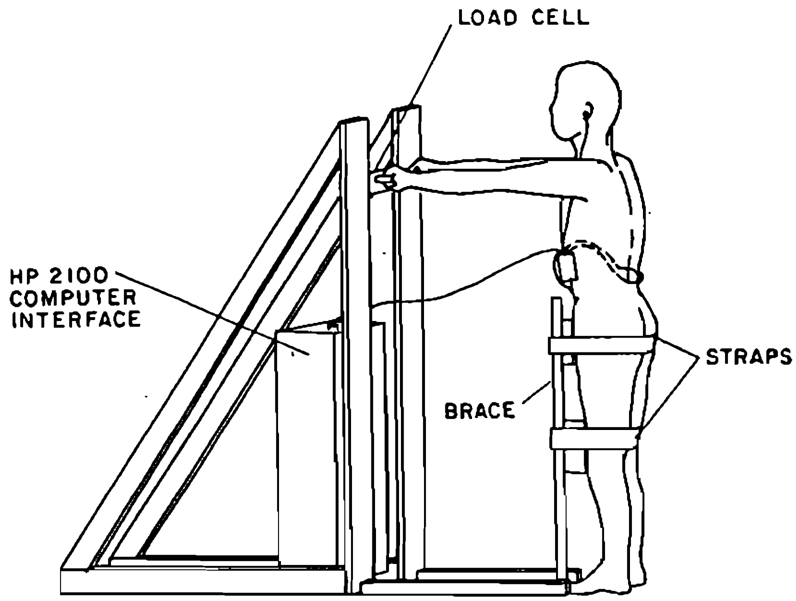

Figure 4. Isometric hand pulling in standing erect posture.

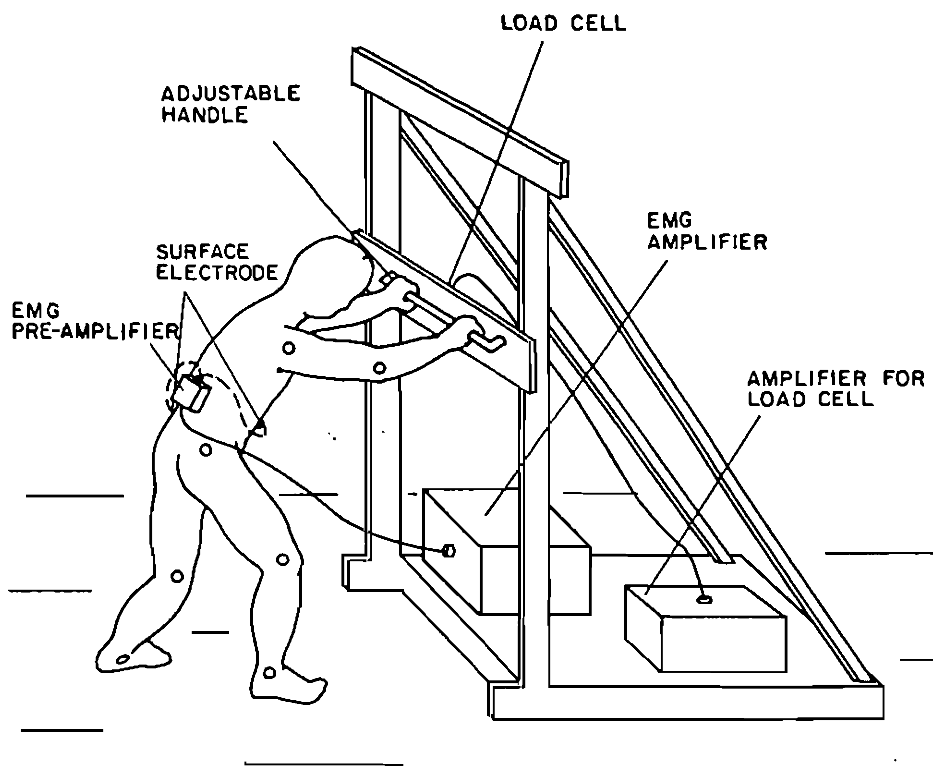

Figure 5. Isometric hand pushing in free posture.

3.3. *Isometric hand pushing and pulling in free postures*

The subjects pushed or pulled a static handle which was set at different heights from the ground (figure 5). The subjects were allowed to assume any posture (free posture) they wanted. The handle heights used were 66, 109 and 152 cm (26, 43 and 60 in.) as used by Snook (1969). This isometric pushing and pulling was also carried out for 4 s and repeated five times. EMG (rms) values were recorded during the continuously increasing pushing and pulling exertion forces. Positions of the body joints were photographed using a 35 mm camera with a strobe flash at 15 Hz for the duration of exertion to capture any changes in the positions as the exertion force varied. For the test of 152 cm high handle, the hip was braced for support to avoid a loss of balance.

4. Subjects

Four male and two female students ranging from 20 to 30 years of age participated in each experiment. All the subjects were healthy and understood the purpose of the experiments. None of the subjects had a history of back pain or previous back trauma. Before the experiment, all subjects were informed and instructed about procedure and possible injuries. The link lengths of the subjects were measured before the experiment using the linear-dimension method (Roebuck *et al.* 1975). Subjects were required to wear shoes with a rubber sole to prevent them from slipping. Table 1 shows the gross anthropometric data of the subjects participating in the experiment.

5. Equipment

A pushing and pulling tester designed and fabricated in the Center for Ergonomics with adjustable handle height was used. The other equipment consisted of the following:

(1) a 35 mm camera with a strobe and a single flash;
(2) an EMG measurement system with an 8-channel amplifier and preamplifiers and nine silver electrodes (two two-electrodes sets for the back, two sets for the abdomen and one set for ground);
(3) an oscilloscope;
(4) a tri-axial load cell and its amplifier;
(5) an 8-channel strip-chart recorder; and
(6) an HP-2100 digital mini computer.

The tri-axial load cell in the handle of the pushing and pulling tester measured the orthogonal forces in horizontal, vertical and lateral directions. This load cell was connected to a carrier amplifier (model 130–2c) to control sensitivity. The amplifier, in turn, was connected via an A/D converter to the HP-2100 mini computer.

Table 1. Subject anthropometry.

Subject	Sex	Stature (cm)	Weight (Kg)
S1	Male	169·0	60·3
S2	Female	162·0	50·0
S3	Male	171·0	75·0
S4	Male	170·5	80·0
S5	Female	169·5	59·1
S6	Male	175·3	62·3

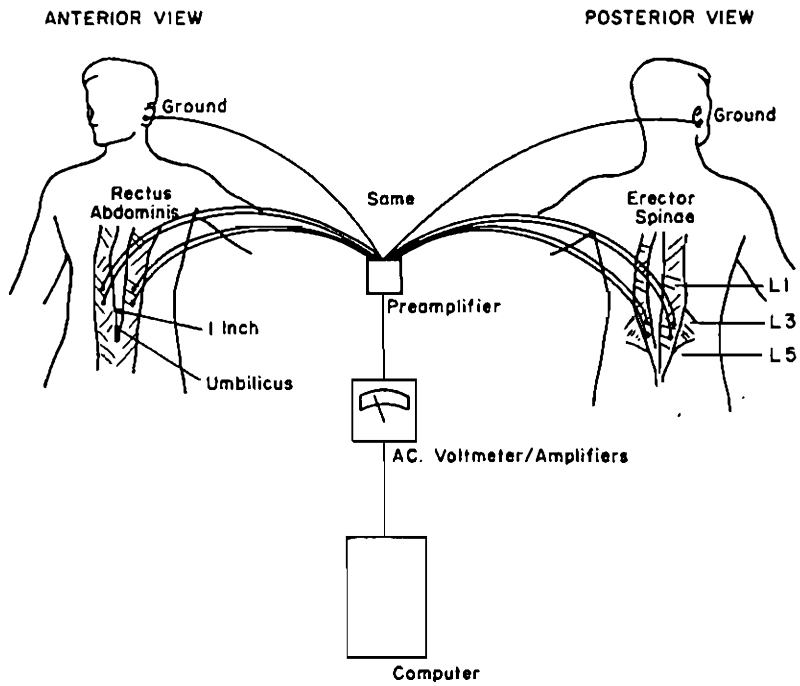

Figure 6. Position of the electrodes on the subject.

The root-mean-square value of EMGs was used to estimate muscle exertion levels. The myoelectrical signals were recorded using bipolar silver electrodes. The positions of electrodes are shown in figure 6. The sampling rate of the EMG signal was 100 Hz which was the same as the sampling rate of the pushing or pulling force.

6. Analysis

Cross correlations were computed between measured EMG (rms) values and predicted muscle forces from the simple model. Parameters of the least square error regression model (linear model) describing the relationship between EMG (rms) values and the predicted muscle forces were computed from the data.for each subject. The statistical model is described below:

$$\text{EMG (rms)} = b_0 + b_1 x_1 + b_2 x_2 + b_3 x_1 x_2 + e \quad (4)$$

where:

EMG (rms) = a root-mean-square electromyogram value (microvolt)
x_1 = muscle force of the erector spinae or the rectus abdominis (newton)
x_2 = indicator variable (0 if pushing, or 1 if pulling)
e = a residual error

b_0, b_1, b_2 and b_3 are least square error fitting parameters.

7. Results

In the experiment involving isometric pushing and pulling of the upper trunk with the thighs and hips braced, the rectus abdominis muscle was active in pushing (figure 7) and inactive in pulling. Exactly the opposite was observed for the erector spinae muscle (figure 8) for all subjects. Figures 7 and 8 show that measured EMG (rms) values were linear and highly correlated (average r-square = 0·93) with the corresponding muscle forces predicted by the simple model. This indicates that the biomechanical model predicts the muscle forces reasonably well in this braced type of pushing and pulling. However, it was noticed that the coefficients of the linear model (Equation 4) varied between subjects as seen in table 2. This type of variation is discussed in detail in Chaffin and Andersson (1984).

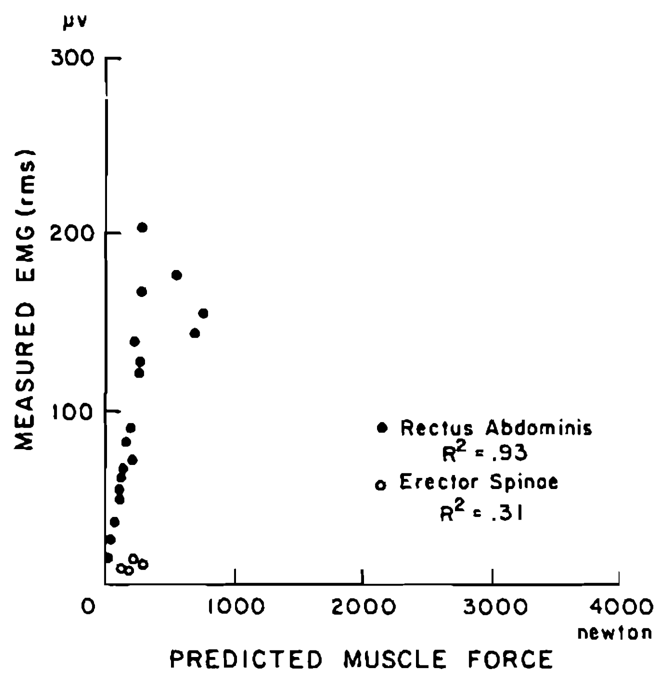

Figure 7. EMG (rms) vs. predicted muscle forces in trunk pushing for all subjects.

Table 2. Least square error regression analysis (Equation 4) of the EMG (rms) amplitude and muscle forces of erector spinae and rectus abdominis in trunk pushing and pulling showing that EMG (rms) amplitudes are different between muscles and subjects.

Subject	Equation	r^2	SE
1	EMG (rms) = $15·67 + 0·085x_1 + 0·005x_2 - 0·078x_1x_2$	0·94	3·5
2	EMG (rms) = $14·2 + 0·145x_1 - 5·2x_2 - 2·54x_1x_2$	0·98	5·7
3	EMG (rms) = $12·74 + 0·208x_1 + 0·776x_1x_2$	0·86	33·1
4	EMG (rms) = $3·5 + 0·069x_1 + 2·5x_2 + 0·010x_1x_2$	0·93	6·4
5	EMG (rms) = $14·97 + 0·088x_1 + 11·152x_2 - 0·042x_1x_2$	0·89	7·5
6	EMG (rms) = $3·85 + 0·421x_1 + 12·4x_2 - 0·030x_1x_2$	0·96	15·1

Note: [1] unit: EMG (rms) (microvolt), muscle force (newton).
[2] x_1: muscle force and $x_2 = 0$ if pushing, 1 if pulling.

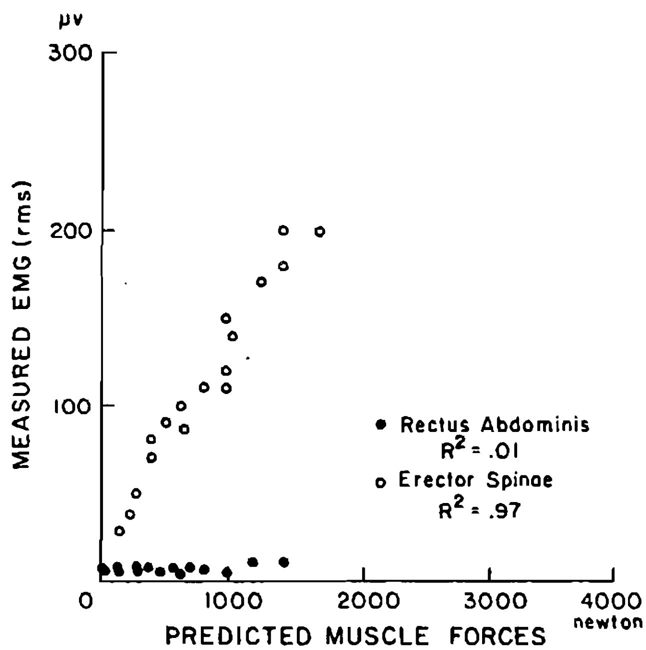

Figure 8. EMG (rms) vs. predicted muscle forces in trunk pulling for all subjects.

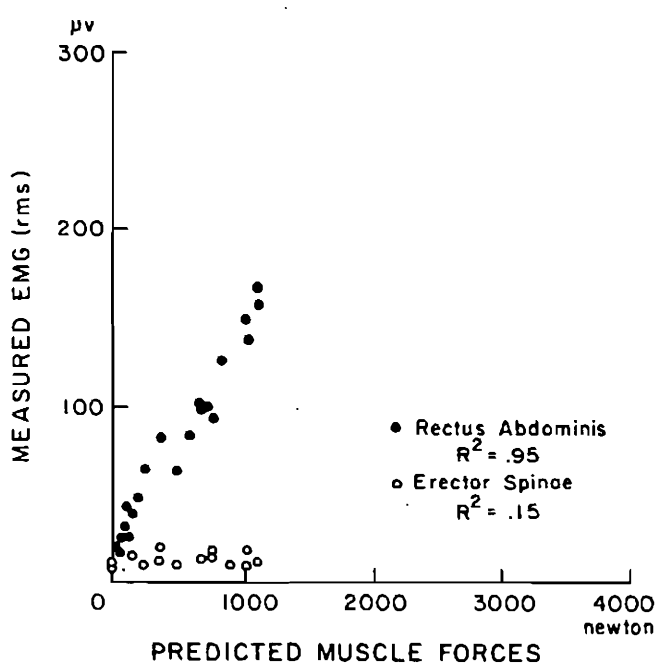

Figure 9. EMG (rms) vs. predicted muscle forces for hand pushing in standing erect posture, for all subjects.

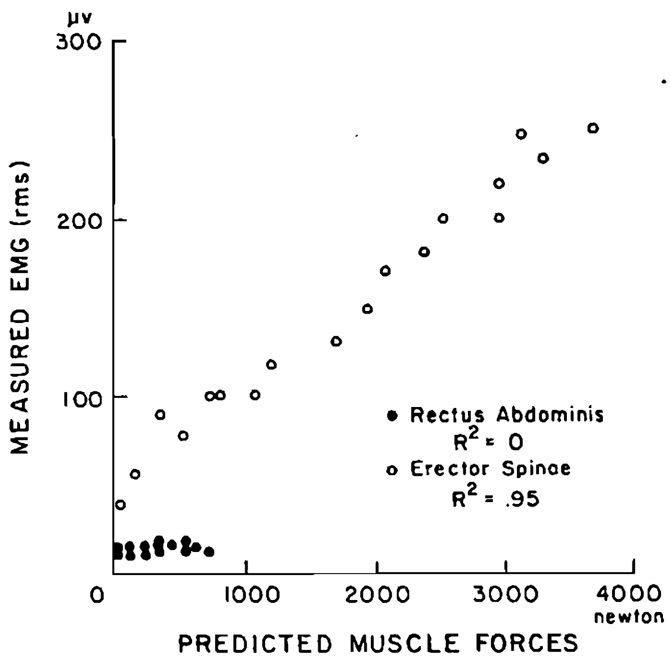

Figure 10. EMG (rms) vs. predicted muscle forces for hand pulling in standing erect posture, for all subjects.

The isometric hand pushing and pulling experiment while standing in an erect braced posture also indicated that measured EMG (rms) values were linearly related (figures 9 and 10) and highly correlated (average $r^2 = 0{\cdot}96$) with the corresponding muscle forces predicted. This also supports the good predictability of lower back stress by the biomechanical model. It was also noticed that the coefficients of the linear model (Equation 4) varied between subjects and within subject. This is evident in table 3.

Table 3. Least square error regression analysis (Equation 4) of the EMG (rms) amplitude and muscle forces of erector spinae and rectus abdominis in hand pushing and pulling (standing erect) showing that EMG (rms) amplitudes are different between muscles and subjects.

Subject	Equation	r^2	SE
1	EMG (rms) = $17{\cdot}851 + 0{\cdot}0821x_1 + 0{\cdot}018x_1x_2$	0·99	7·5
2	EMG (rms) = $19{\cdot}6 + 0{\cdot}016x_1 - 3{\cdot}5x_2 + 0{\cdot}20x_1x_2$	0·94	9·8
3	EMG (rms) = $-2{\cdot}095 + 0{\cdot}068x_1 + 26{\cdot}13x_2 + 0{\cdot}479x_1x_2$	0·95	20·9
4	EMG (rms) = $7{\cdot}344 + 0{\cdot}015x_1 + 0{\cdot}022x_1x_2$	0·98	6·7
5	EMG (rms) = $14{\cdot}9 + 0{\cdot}033x_1 - 6{\cdot}5x_2 + 0{\cdot}143x_1x_2$	0·94	8·9
6	EMG (rms) = $15{\cdot}12 + 0{\cdot}125x_1 - 16{\cdot}99x_2 - 0{\cdot}064x_1x_2$	0·95	13·0

Note: [1] unit: EMG (rms) (microvolt), muscle force (newton).
[2] x_1: muscle force and $x_2 = 0$ if pushing, 1 if pulling.

Table 4. Correlations between EMG (rms) values and predicted muscle forces in each experiment for each subject.

	Experiment (pushing and pulling)				
		Hand in erect posture	Hand in free posture		
			Handle height (cm)		
Subject	Trunk		66	109	152
S1	0·94	0·99	0·31	0·23	0·19
S2	0·98	0·94	0·45	0·55	0·46
S3	0·86	0·95	0·32	0·49	0·53
S4	0·93	0·98	0·28	0·25	0·19
S5	0·89	0·94	0·32	0·41	0·44
S6	0·96	0·95	0·62	0·17	0·48

However, the results from the hand pushing and pulling in the free standing postures were different from the above findings. Measured EMG (rms) values were neither linear nor well-correlated (table 4) with the corresponding muscle forces predicted, and did not show any consistent pattern (average $r^2 = 0{\cdot}37$).

8. Discussion

Several explanations may be offered for the low correlations observed between EMG (rms) values and predicted muscle forces. First, this may be due to the interaction with other muscle groups, such as the abdominal oblique muscles. Or it may be due to the interference of the EMG signals caused by ligamentous contributions (Farfan 1975, Shultz *et al.* 1982) when the torso is flexed. This problem may also be caused by the fact that the spinal ligaments can contribute tension only if the torso flexion is great. Also when the muscle length becomes much longer than its resting length, passive muscle tension becomes significant. The results show that as the upper torso flexion angle becomes bigger, the EMG (rms) value increases. This is expected because, as the torso flexion angle becomes bigger the erector spinae muscle forces increase. This increase can be explained since the flexion turning moment due to gravity acting on the upper body increases as the moment arm of the upper torso is increased. However, it was found that EMG (rms) value starts to decrease as the torso flexion angles become greater than 45°. Passive muscle and spinal ligament tension can cause the low EMG (rms) values for high muscle forces in the low handle pushing and pulling. Similar findings were reported by Schultz *et al.* (1985) but they found the peak angle at 30° instead of 45°.

Figure 11 shows the relationship between EMG (rms) values and the torso flexion angles. An equation derived for this relationship using the polynomial regression method was:

$$\text{EMG(rms)} = 7{\cdot}2 + 2{\cdot}17\ \text{angle} - 0{\cdot}023\ \text{angle}^2$$

where:

EMG(rms) = a root-mean-square electromyogram value in microvolt.
Angle = the torso flexion angle in degree.

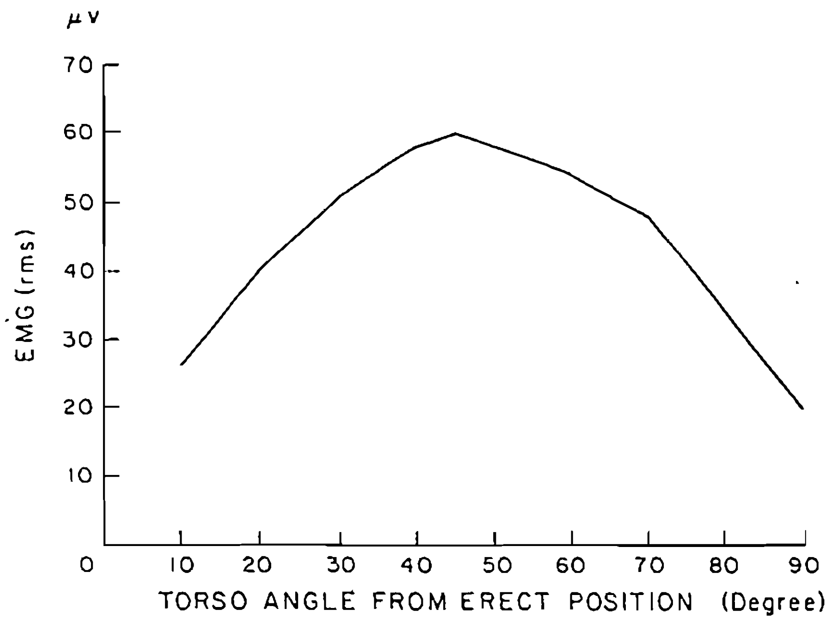

Figure 11. EMG (rms) vs. torso flexion angle in bending with free hand, for all subjects.

Lastly, it may be due to the model which can not predict the muscle force with quantitative precision (Marras 1983, Shultz *et al.* 1982). Tasks involving flexion and extension of the back tend to recruit various trunk muscles. A simple biomechanical model with only one muscle active at a time may not be appropriate for the estimation of the muscle forces on the lower back when complex torso actions are involved.

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References

ANDERSON, C. K. and CHAFFIN, D. B. 1984, A biomechanical evaluation of five lifting techniques, *Proceedings, Int. Conf. on Occupational Ergonomics* (Toronto) 313–317.

ANDERSSON, G., ORTENGREN, R. and SHULTZ, A. 1980, Analysis and measurement of the loads on the lumbar spine during work at a table, *J. of Biomechanics*, **13**, 513–520.

AYOUB, M. and MCDANIEL, J. 1974, Effects of operators stance pushing and pulling tasks, *AIIE Transactions*, **6**, 185–195.

CHAFFIN, D. B. and ANDERSSON, G. B. J. 1984, *Occupational Biomechanics* (John Wiley & Sons, New York).

CHAFFIN, D. B., ANDRES, R. O. and GARG, A., 1983, Volitional postures during maximal push/pull exertions in the sagittal plane, *Human Factors*, **25**, 541–550.

CHAFFIN, D. B. 1972, Some effects of physical exertion, Western Electric Project Report, The University of Michigan.

CHAPMAN, A. E. and TROUP, J. D. G. 1969, The effect of increased maximal strength on the integrated electrical activity of lumbar erector spinae, *Electromyography*, **9**, 263–280.

DEMPSTER, W. T., SHERR, L. A. and PRIEST, J. G., 1964, Conversion scales for estimating humeral and femoral lengths and the lengths of functional segments in the limbs of American caucasoid males, *Human Biology*, **36**, 246–261.

FARFAN, H. F. 1975, Muscular mechanism of the lumbar spine and the position of power and efficiency, *Orthop. Clinic of N. Amer.*, **6**, 135–144.

GAUGHRAN, G. R. L. and DEMPSTER, W. T. 1956, Force analysis of horizontal two-handed pushes and pulls in the sagittal plane, *Human Biology*, **28**, 69–92.

KROEMER, K. H. E. 1974, Horizontal push and pull forces, *Applied Ergonomics*, **5**, 94–102.

LEE, K. S. 1982, Biomechanical modelling of cart pushing and pulling, Ph.D. Dissertation, Center for Ergonomics, University of Michigan.

MARRAS, W. S. 1983, A model-experiment comparison of loads on the lumbar spine, *Proc. of the Human Factors Society, 27th Annual Meeting*, **1**, 284–288.

PARK, K. S. and CHAFFIN, D. B. 1974, A biomechanical evaluation of two methods of manual lifting, *AIIE Transactions*, **6**, 105–113.

ROEBUCK, J. A., KROEMER, K. H. E. and THOMPSON, W. G. 1975, *Engineering Anthropometry Methods* (John Wiley & Sons, New York).

SHULTZ, A., ANDERSSON, G. B. J., HADERSPECK, K., ORTENGREN, R., NORDIN, M. and BJORK, R. 1982, Analysis and measurement of the lumbar trunk loads in tasks involving bends and twists, *J. of Biomechanics*, **15**, 669–675.

SHULTZ, A., HADERSPECK, K., SINKORA, G. and WARWICK, D. 1985, Quantitative studies of the flexion-relaxation phenomenon in the back muscles, *J. Orthop. Res.*, **3**, 189–197.

SNOOK, S. H., IRVINE, C. H. and BASS, S. F. 1969, Maximum weights and workloads acceptable to male industrial workers while performing lifting, lowering, pushing, pulling, carrying and walking tasks, *Proc. of the Amer. Ind. Hyg. Conf.* (Denver, Colorado).

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