

Sitting posture: analysis of lumbar stresses with upper limbs supported

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The analysis of lumbar stresses in the sitting posture is performed for situations in which upper limbs are fully or partially supported by a worktable. A method is presented for biomechanical evaluation of moments and compressive forces acting on the lumbar intervertebral disk, based on the use of a force platform, a TV camera and a integrated system for the elaboration of signals. The on-line pictures given by this equipment show the ground reaction vector superimposed on the subject's image and allows a detailed analysis of the intervertebral loads. The results obtained in the subjects under study (six males and five females) are analysed statistically and extrapolation on the basis of body weight is demonstrated to be possible in situations where the arm support forces are not known. The myoelectric activity of the erector spine muscles was also assessed.

The aim of the study was to furnish a tool that can be used in all occupational environments and that will allow evaluation of the lumbar stresses in the sitting posture to be made with a minimum use of complex equipment. An example of the practical application of this concept is presented.

1. Introduction

In order to assess the tolerability of a given posture measurement of lumbar stresses is important. The stresses are generally expressed in terms of forces and moments acting on a given articulation of the lumbar spine and in particular on its intervertebral disk. Several methods are described in the literature for calculating these mechanical actions, ranging from biomechanical analysis based on mathematical models or electromyographic investigation and direct measurements of the intradiscal or intra-abdominal

pressure (Andersson et al. 1977, 1978, 1980, Chaffin 1982, Davis, 1981, Eklund et al. 1983, Colombina et al. 1985, Nachemson 1981, Ortengren et al. 1981, Schultz and Andersson 1981, Schultz et al. 1982 a, b). Nevertheless, no application procedure for analysis of the compressive loads on the lumbar disk has been reported for situations in which the upper limbs are partially or fully supported by a worktable. Such situations are very common in industry and merit treatment in a specific study. In fact, the situations usually illustrated in the literature, i.e. sitting upright using a backrest, head straight and arms hanging, are rather different from the situation in which the upper limbs are supported and a new distribution of forces is thus produced.

The aims of this study were:

- (1) Quantification of the above phenomena in different trunk positions and with varying support of the upper limbs.
- (2) Illustration of a procedure for calculating the lumbar stresses (at the L3—L4 level) in well-defined situations.

2. Methods

2.1. Experimental procedure

Eleven healthy volunteers were analysed (six men and five women). The average weight was 74.5 kg (S.D. = 10) for the males and 59.7 kg (S.D. = 3.8) for the females, and the average height was 172 cm (S.D. = 8.9) and 165.8 cm (S.D. = 8.9) respectively. The subjects were asked to sit on a chair with an adjustable seat-height and type on the keyboard of a personal computer placed on a table 75 cm high.

Three different trunk positions were studied (table 1, figure 1):

- (1) straight,
- (2) kyphotic (correction of lumbar lordosis with pelvis slightly rotated forwards),
- (3) bent forward (20-30°).

For each position four typical arm conditions were considered:

- (1) arms hanging,
- (2) no arm support (while typing on keyboard),
- (3) light support (resting only on wrists),
- (4) full support (resting on full forearm).

These twelve situations were reproduced by adjusting the distance between the subject and the table and from the subject to the keyboard, and will be referred to by the codes reported in table 1.

The myoelectric activity of the lumbar back muscles at the L3 level was analysed and compared with the maximal voluntary contraction (MVC) against resistance measured in the prone position. The lumbar stresses were calculated in each seated condition by appropriate elaboration of signals from a force platform and a television system.

Table I. Codification and description of the 12 positions examined.

| Position code | Trunk | Upper limbs |
|---------------|----------|-------------------------|
| 1.1 | Straight | Hanging |
| 1.2 | Straight | Extended, no support |
| 1.3 | Straight | Extended, light support |
| 1.4 | Straight | Extended, full support |
| 2.1 | Kyphotic | Hanging |
| 2.2 | Kyphotic | Extended, no support |
| 2.3 | Kyphotic | Extended, light support |
| 2.4 | Kyphotic | Extended, full support |
| 3.1 | Bent | Hanging |
| 3.2 | Bent | Extended, no support |
| 3.3 | Bent | Extended, light support |
| 3.4 | Bent | Extended, full support |

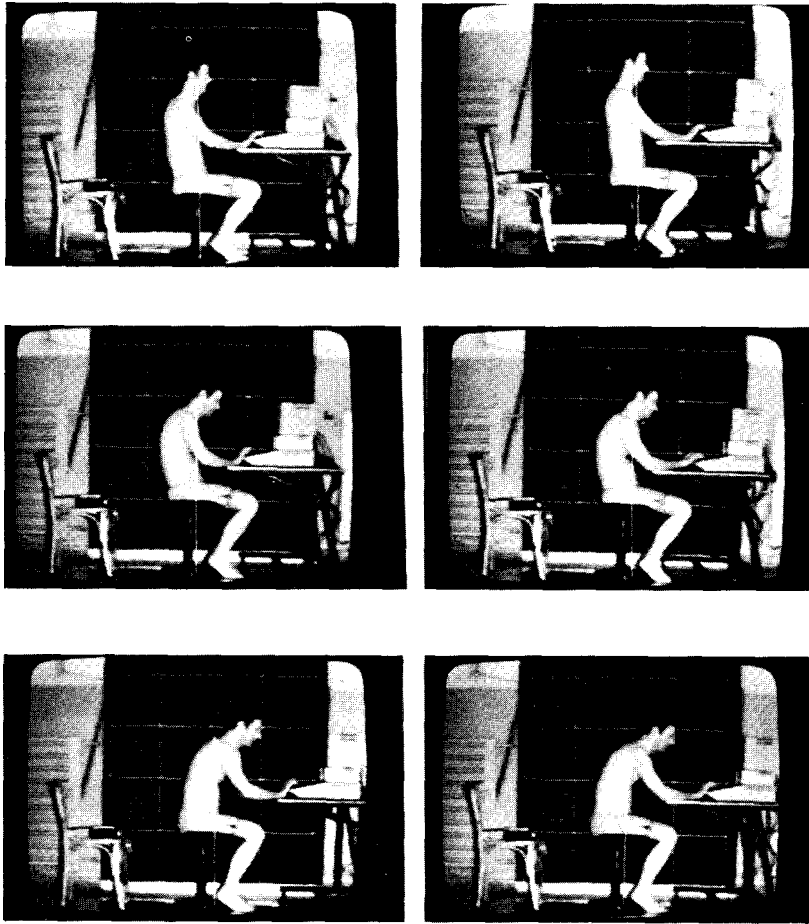


Figure 1. Positions in which upper limbs were supported: pictures from the tv monitor.

2.2. Equipment

A piezoelectric force platform (Kistler 9261A) was mounted on the floor under the chair (Boccardi *et al.* 1977, Pedotti 1977), and was large enough (40-60 cm) to allow the subject to accommodate his feet on the platform in all the situations examined.

Posture geometry was detected by a TV camera which provided the lateral view of the subject. A special purpose device (Digivec) elaborated the signals from the force platform so as to compute, on-line, the amplitude, the inclination and the point of application of the ground reaction resultant, and superimpose the image of the vector, on an appropriate scale, on the image of the sitting subject (Ambrosini *et al.* 1983). Retroreflective markers applied to the main reference points on the subject, made for better identification of the anatomical segments and their centres of gravity.

The resultant images were recorded on a videotape and further elaborations were performed on single frames photographed from a TV monitor. An example of the images obtained is given in figure 1 for the positions with arms supported that were analysed.

The myoelectric activity of the muscles was obtained by surface electrodes connected to a telemetric device. Signals were rectified and integrated on-line by an analog device (time constant 50 ms) and fed into a paper recorder (SAN-EI VISIGRAPH 5L).

2.3. Biomechanical evaluation of lumbar stress

If it is assumed that the subject's body is divided by a horizontal plane crossing the intervertebral disc between L3 and L4, on the basis of the images previously obtained and by making some assumptions, it is possible to calculate the lumbar stresses in two distinct ways.

The first, more direct method, utilizes the information on amplitude, inclination and position of the ground reaction vector furnished by the TV recordings. It considers the part of the body below L3 and consists of imposing a static equilibrium of the moments expressed by the following equation:

$$M_{L3} - R X_R + \sum_j W_j X_j = 0 \rightarrow M_{L3} = R X_R - \sum_j W_j X_j \quad (1)$$

where M_{L3} is the moment at L3 (clockwise [c.w.] positive), R is the ground reaction force, X , is the distance of R from L3, W , is the weight of the i th anatomical segment below L3 and X_i is the distance of its centre of gravity from the vertical line crossing L3.

The second method deals with the upper part of the body and gives:

$$M_{L3} = \sum_j W_j X_j + F X_F, \quad M_{L3} = \sum_j W_j X_j - F X_F \quad (2)$$

where M_{L3} is the moment at L3 (counter clockwise [c.c.w.] positive), F is the arm support force and X_F is its distance from L3, W_j is the weight of the j th segment above L3 and X , is the distance of its centre of gravity from L3.

If we consider that, for the equilibrium of the whole body,

$$R X_R = \sum_i W_i X_i + \sum_j W_j X_j - F X_F \quad (3)$$

we obtain

$$M_{L3} = \sum_j W_j X_j + W X, - F X_F - \sum_i W_i X_i$$

$$\sum_j W_j X_j - F X_F = M_{L3} \quad (4)$$

Therefore, in principle, the results obtainable by the two methods should be the same.

In practice the parameters required by the first method are all easily measurable on images obtained using the equipment or can be derived from anthropometric tables, while with the second method F and X_F are not known. Nevertheless, taking into account that the equipment described above is a prototype not generally available to operators, care was taken to identify all possible assumptions that could allow an evaluation of the L3 moment with the minimum of equipment required. For this purpose the second method proved to be more applicable.

In fact, after careful examination of the different situations, it was possible to draw the following considerations:

- (1) The amplitude of the arm support force is obtainable from the difference between the subject's weight and the ground reaction measured by the force platform (or, alternatively, by a dynamometer properly adjusted on the table).
- (2) The lever arm can be easily estimated from the lateral view of the subject by analysing the contact area between the forearms and the table (in positions 1.3, 2.3 and 3.3 the contact area is the wrist, in positions 1.4, 2.4 and 3.4 the support point was identified a few centimetres from the elbow).
- (3) In equation (2) the prevalent term on the right was

$$\sum_j W_j X_j$$

and thus an error in the estimation of F_X affects the total result by a small percentage (consider also that error in the estimation of

and
$$\sum_j W_j X_j$$

$$\sum_i W_i X_i$$

are unavoidable and are basically equivalent in the two cases).

The following are the equations adopted by the second method (upper body considered) (figure 2):

$$M_{L3} = M_a + M_b + M_c + M_d + M_e + M_f - (mg) \tag{5}$$

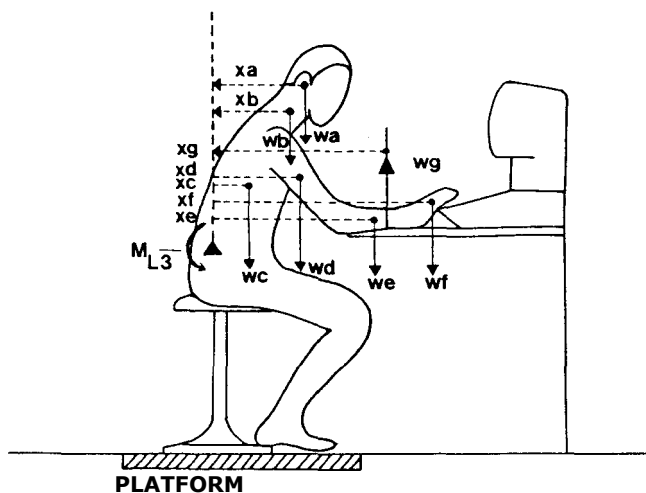


Figure 2. Scheme for the computation of lumbar stress using the second method described in the text.

where

$$M_i = W_i X_i, \quad M_b = W_b X_b, \quad \text{etc.} \quad (6)$$

$$F_{ML3} = M_{L3} / l, \quad (7)$$

$$P_{L3} = F_{ML3} + (W_g - W_g \cos \alpha) \quad (7)$$

M_{L3} is the resultant moment at the L3 level, M_a, M_b, \dots, M_f are the moments of the segments about L3 (a = head, b = neck, c = trunk, d = arms, e = forearms, f = hands), M_i is the moment of the arm support force about L3, X_i, X_{i+1}, \dots, X_f are the distances of the barycentre of each segment from the vertical line crossing L3, W_i, W_{i+1}, \dots, W_f are the weights of each of the segments above L3, W_g is the weight of the part of the body above L3 (57% of total body weight), W_g is the arm support force, α is the forward bending angle of the lumbar spinai tract with respect to the vertical, F_{ML3} is the force required by the erector spinae muscles and P_{L3} is the resultant compressive force on the L3—L4 intervertebral disk.

As can be seen, the force required for the erector spinae muscles to sustain the calculated moment is obtained by dividing this moment by the lever arm of the muscles themselves (assumed to be 5 cm) presuming that no other mechanisms such as intra-abdominal pressure intervene. The compressive force on the intervertebral disk is the sum of the force exerted by the erector spinae muscles and the projection of the weight of the upper part of the body (above the horizontal plane crossing L3—L4) in the direction of the lumbar spine (perpendicular to the disk).

In brief, the elaboration proceeded by the following steps:

- (1) Determination of the weights of all anatomical segments above L3 by scaling the anthropometric values reported in the literature (Dempster 1955) to the subject's weight.
- (2) Measurement of the distances between the centre of gravity of all the anatomical segments and the vertical line crossing L3.
- (3) Determination of the arm support force from the difference between the whole body weight and the ground reaction force measured in each condition.
- (4) Estimation of the position of the arm support force and measurement of the distance from the vertical line crossing L3.
- (5) Calculation of M_{L3}, F_{ML3} and P_{L3} by formula (5H7).

The same variables were also calculated under the theoretical hypothesis that, in each position with arms supported, no force was exerted on the table. This was made by suppressing the terms ' M_g ' in equation (5) and ' W_g ' in equation (7). In practice this is the only calculation that can be made without the use of a dynamometric device. By analysis of the two series of data for the various subjects examined, a linear regression line was obtained together with the confidence limits to be adopted for new estimations.

3. Results and discussion

Figure 3 shows the mean values of the arm support forces, expressed as a percentage of the body weight, for the different situations, and the standard deviation above and below the mean. In each trunk position the mean percentage values of the force were greater in the fully supported conditions. Furthermore, these values, which were very similar in the erect and kyphotic-trunk conditions, increased in the flexed-trunk position.

Table 2 gives the loads calculated for each subject, at L3 (expressed in kilograms) in each of the postures with the arms supported. The X columns are the values obtained

Table 2. Discal loads (on L3) for each subject, in supported upper limbs postures. The values are computed by assuming the arm support force to be (a) equal to 0 (X columns) and (b) as actually measured (Y columns).

| Subject | (kg) | | (cm) | | 1.3, straight, light support Weight | | 1.4, straight, full support Height | | 2.3, kyphotic, light support | | 2.4, kyphotic, full support | | 3.3, bent, light support | | 3.4, bent, full support | |
|--------------------|------|---|-------|---|---|------|--|------|---------------------------------|-------|--------------------------------|-------|-----------------------------|-------|----------------------------|-------|
| | | | | | X | Y | X | Y | X | Y | X | Y | X | Y | | |
| SA 3 | 63 | n | 161 | n | 131 | 124 | 132 | 106 | 133 | 103 | 159 | 101 | 195 | 110 | 195 | 94 |
| FE j | 69 | | 171 | | 108 | 74 | 120 | 78 | 125 | 99 | 131 | 90 | 189 | 165 | 210 | 146 |
| MA 3 | 85.5 | | 184 | | 114 | 93 | 134 | 120 | 188 | 175 | 257 | 226 | 292 | 223 | 297 | 177 |
| PA j | 88.5 | | 179 | | 206 | 167 | 210 | 153 | 215 | 178 | 216 | 157 | 295 | 195 | 335 | 140 |
| PO d | 68 | | 163 | | 115 | 81 | 125 | 75 | 136 | 114 | 141 | 93 | 196 | 122 | 215 | 102 |
| TA d | 73.5 | | 174 | | 146 | 113 | 148 | 109 | 184 | 143 | 190 | 137 | 240 | 145 | 257 | 129 |
| LA | 57 | | 165 | | 89 | 82 | 11• | 85 | 137 | 116 | 143 | 117 | 151 | 126 | 174 | 131 |
| PT | 56 | | 156 | | 80 | 70 | 89 | 63 | 101 | 92 | 119 | 96 | 120 | 102 | 143 | 103 |
| FO | 64 | | 168 | | 108 | 94 | 115 | 84 | 134 | 109 | 153 | 110 | 178 | 118 | 191 | 105 |
| CO | 58 | | 167 | | 105 | 94 | 116 | 109 | 122 | 107 | 131 | 107 | 167 | 128 | 131 | 120 |
| CA | 63.5 | | 173 | | 102 | 85 | 125 | 92 | 131 | 121 | 153 | 110 | 169 | 136 | 187 | 100 |
| Mean values | 74.5 | j | 172 | j | 118.5 | 97.9 | 129.6 | 97.6 | 146 | 128.3 | 163 | 122.2 | 199.3 | 142.7 | 217 | 122.5 |
| | 59.7 | | 165.8 | Y | | | | | | | | | | | | |
| Standard deviation | 10 | d | 8-93 | | 35.7 | 29.3 | 30.5 | 25.2 | 34.2 | 29.4 | 41.8 | 39.7 | 55.3 | 37.4 | 56.6 | 25.2 |
| | 3.76 | | 8.9 | Y | | | | | | | | | | | | |

Sitting posture

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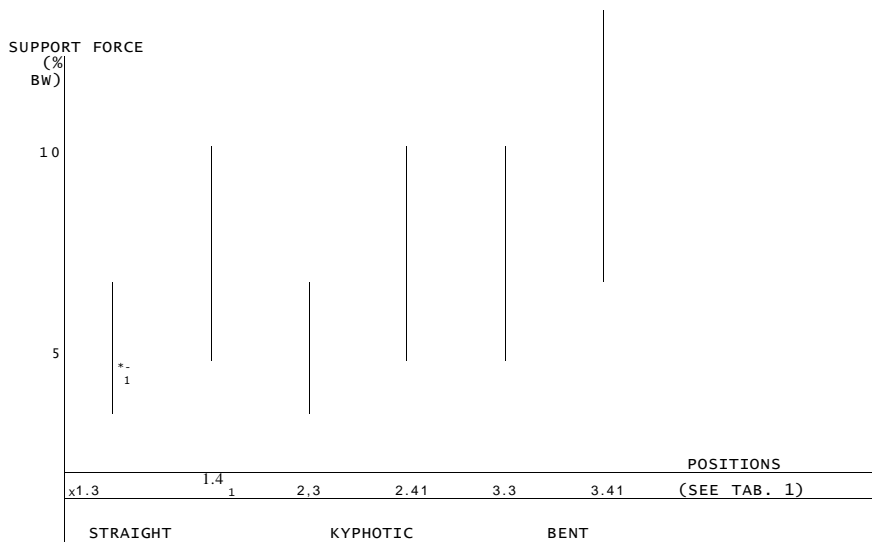
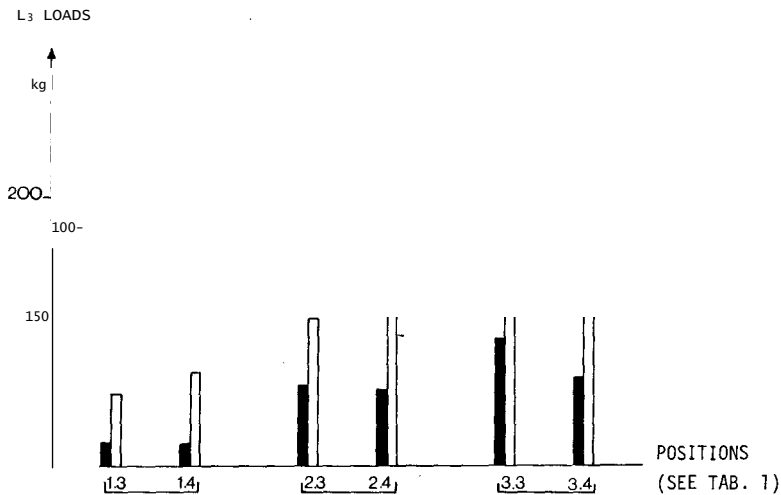


Figure 1 Mean values and standard deviation of the upper limbs support force percentage of body weight (BW).



assuming the arm support force to be nil and the *Y* columns are the values obtained considering the force values as calculated above.

In figure 4 the mean values from table 2 are shown for all of the positions with arms supported (white columns: *X* values; black columns: *Y* values). With the trunk in an upright or kyphotic position full support of the arms produces, substantially, the same values of intervertebral stress as in the lightly supported position; the reduction compared with the theoretical situation of no support force is more marked in the full support position. The results are quite different in the flexed-trunk position, where the fully supported condition produces lower values of intervertebral stress compared with the lightly supported condition; in this case the stress is similar to that in the kyphotic

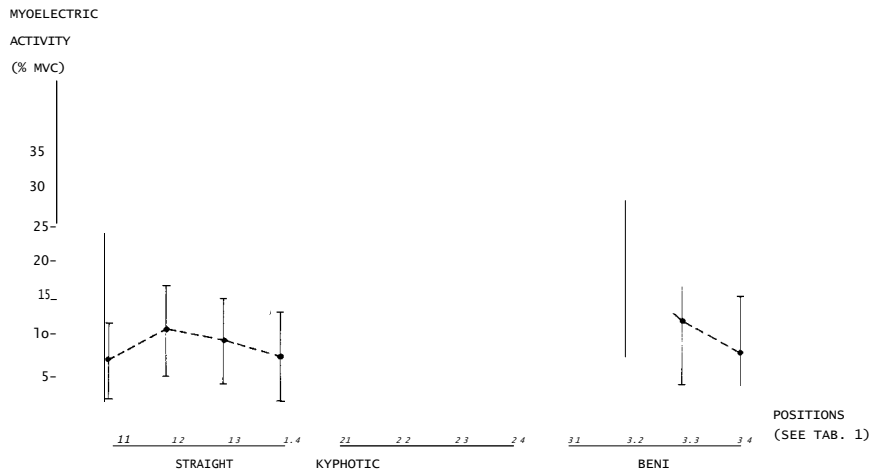


Figure 5. Mean values and standard deviation of lumbar myoelectric back muscles activity (% MVC).

position of the trunk. Referring to the postural situations represented by the white columns it can also be observed that the 1.3 and 2.3 conditions (no support force) correspond to situations that are common in many workplaces.

Figure 5 shows the mean and standard deviation values of the myoelectric activity of the lumbar back muscles expressed as a percentage of the MVC against resistance. It can be observed that for each trunk position muscle involvement is greater when the arms are unsupported. In the different trunk positions the highest myoelectric activities were recorded when the trunk was flexed (3.1, 3.2, 3.3, 3.4), and the lowest when the trunk was in a kyphotic position. These data are of great interest because they do not directly reflect the behaviour of the lumbar stress which, on the contrary, increases in kyphotic conditions compared with the upright positions.

The hypothesis accepted by many authors (Ortengren *et al.* 1981, Schultz *et al.* 1982 a) of a direct and linear correlation between muscular contractile activity and lumbar stress is confirmed when considering and comparing straight and beni conditions of the trunk but appears to be inadequate for evaluating lumbar stress in kyphotic conditions of the trunk. It is the opinion of the writers that dorsal kyphosis, accompanied by the disappearance of lumbar lordosis (note that the pelvis is not blocked and can thus rotate forward), produces a stretching of the erector spinae muscles that, in these conditions, can exert the required force without any appreciable active contraction. Furthermore, passive structures such as the intervertebral ligaments, are involved in supporting lumbar stress, giving rise to a phenomenon similar to that already observed in the upright standing posture with the trunk flexed to the maximum when lifting a weight (Colombina *et al.* 1985).

Figure 6 (a) and (b) shows the regression lines obtained by considering the lumbar stress (P_{13} expressed in kilogrammes) calculated by both taking into account the arm support force (values on the y axis and by neglecting them (x axis). In figure 6 (a) the regression lines are obtained by pooling the results in the upright and kyphotic trunk positions; the continuous line corresponds to light support and the dashed line to full support of the arms. Figure 6 (b) shows the flexed-trunk position with light arm support (continuous line) and full support (dashed line). The hypothesis of linearity can be accepted in all cases ($p < 0.001$ except in the case of flexed trunk with arms fully

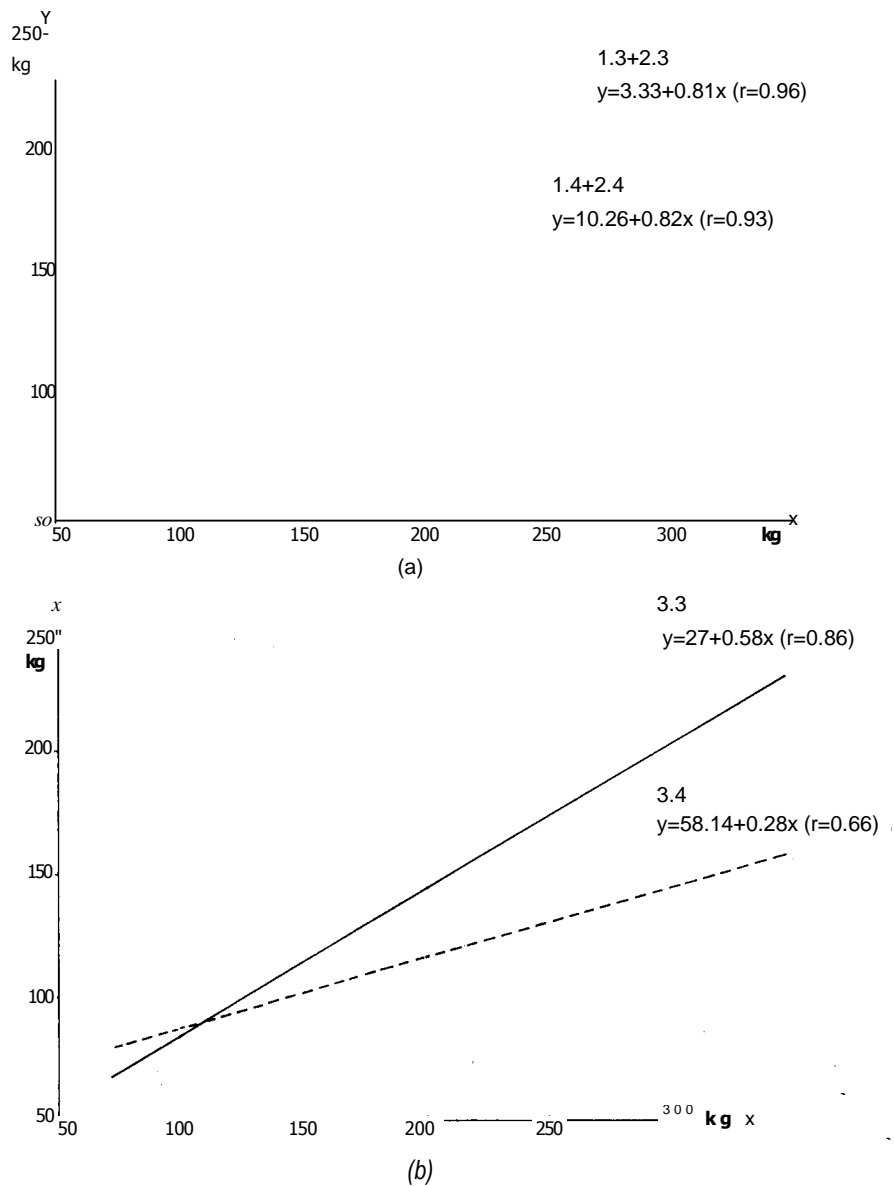


Figure 6. (a) Relation between discal load values computed by assuming the arm support force = 0 (X) and arm support force as actually measured (Y). The continuous line refers to positions 1.3 and 2.3; the dashed line refers to positions 1.4 and 2.4. (b) Relation between discal load values computed by assuming the arm support force = 0 (X) and arm support force as actually measured (1). The continuous line refers to position 3.3; the dashed line refers to position 3.4.

supported where $p < 0.02$). Taking account of the prediction errors in the regression parameters and the variability of the sampled data, the 95% confidence limits were calculated in order to predict PL_3 values in kilogrammes in arm-supported conditions when the lumbar stress is only known for the theoretical case of no force exerted by the upper limbs.

In the various situations the above analysis yields:

| | | |
|-------------|-----------------------|-----------------|
| 1.3 or 2.3: | $Y = 3.33 + 0.81x,$ | $y = \pm 20.7,$ |
| 1.4 or 2.4: | $y = -10.26 + 0.82x,$ | $y = \pm 23.8,$ |
| 3.3: | $y = 27 + 0.58x,$ | $y = \pm 33.9,$ |
| 3.4: | $y = 58.14 + 0.28x,$ | $y = \pm 33.5.$ |

The fairly high range of these prediction limits is due to a relatively high residual variance, in particular with regard to the flexed-trunk positions. It should be noted here that a variability was observed amongst the different subjects in correctly assuming the posture. In fact, no restraints were imposed on the subjects, who could, for example, assume a kyphotic position with a forward displacement of the center of gravity of the trunk at an angle ranging from 0 to 15° from the vertical. In the flexed-trunk condition forward bending ranged in general between 20 and 30°. Also, the concept of light support and full support of the arms was subject to individual interpretation.

The above remarks are supported by the following observations:

- (1) The arm support force is well correlated with the forward bending angle of the trunk both in light support and full support conditions (see the regression lines shown in figure 7).
- (2) The arm support force, mainly in the flexed-trunk condition, shows a linear inverse relationship with the muscular involvement of the lumbar back muscles (see figure 8). This means that some of the subjects assume a more supported position, thus requiring less muscular activity, while others do not support their arms so much and supported the trunk mainly by the lumbar back muscles.

In this context, however, it is important to recall that individual variability in assuming the instructed position cannot usually be avoided in practical situations of workplace

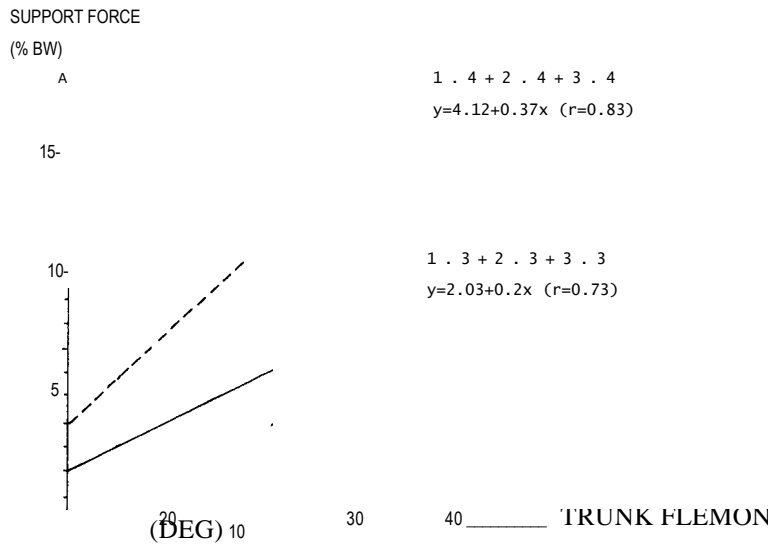


Figure 7. Relation between upper limbs support force (percentage of body weight) and degree of trunk flexion. The continuous line refers to positions 1.3, 2.3, 3.3; the dashed line refers to positions 1.4, 2.4, 3.4.

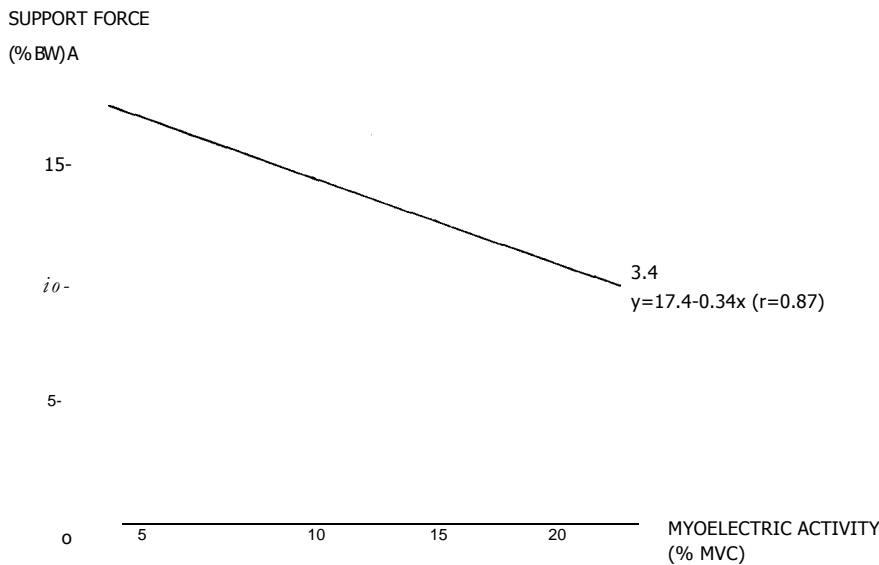


Figure 8. Relation between upper limbs support force (percentage of body weight) and lumbar myoelectric back muscle activity (% MVC) in 3.4 position.

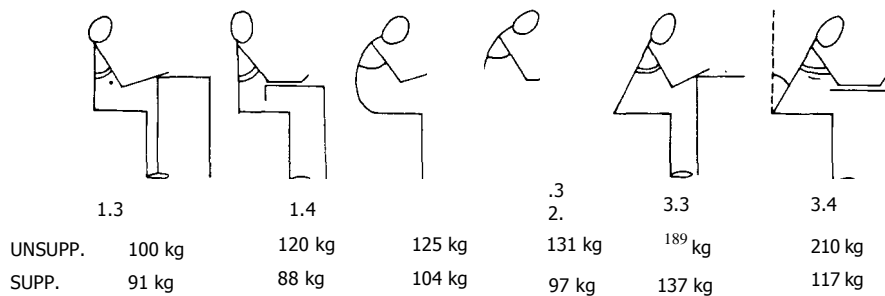


Figure 9. Discal loads (kg) computed in an average subject (weight 70 kg, height 1.70 m) by using the regression lines in figure 6 (a) and (b).

analysis. It was therefore preferred to keep the prediction limits high with a view to their practical application.

Finally, it is thought useful to summarize the procedure for estimating the lumbar stresses (P_{13} in kilogrammes) in sitting postures, with the arms supported, in all practical situations in which it is impossible to calculate the arm support force directly. It consists of the following steps:

- (1) Schematic representation of the posture in the sagittal plane.
- (2) Calculation of the lumbar stress (P_{13} , in kilogrammes), according to the mathematical model described in §2.3, neglecting the arm support forces.
- (3) Estimation of the corresponding P_{13} value (and of the relative confidence limits) in the real situation of arm support by means of the regression lines described above and reported in figure 6 (a) and (b). As an example of this procedure, figure 9 reports the referente values of lumbar stresses (in kilogrammes) calculated in the different positions examined for a subject of 70 kg weight and 170 cm height.

4. Conclusion

The use of the original equipment described in § 2 allowed values of the arm support forces exerted on the worktable in different sitting postures commonly found in the occupational environment to be obtained. By means of a mathematical model based on biomechanical concepts, the lumbar intervertebral stresses could be calculated from these values. In such a way it was possible to observe that arm-supported conditions produce a reduction in lumbar stresses compared with corresponding non-supported-arm conditions ranging from about 15% with straight or kyphotic trunk to 30% or more when the trunk is bent forward by about 20-30°.

Furthermore, a good correlation was demonstrated between lumbar stress values obtained by respectively considering and neglecting the arm support force in all the positions considered. In this way it is possible to estimate the lumbar stresses in the seated posture with arms supported in all practical situations in which no sophisticated equipment is available.

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L'analyse des contraintes lombaires dans la position assise est effectuée dans des situations où les membres supérieurs sont totalement ou partiellement supportés par une table de travail. Une méthode est présentée pour une évaluation biomécanique des moments et des forces de compression agissant sur le disque intervertébral lombaire. Cette méthode utilise une plateforme de force, une caméra de T.V. et un système intégré pour l'élaboration des signaux. Le dessin en ligne fourni par cet équipement montre le vecteur réactionnel de base surimprimé à l'image du sujet et permet une analyse des charges intervertébrales. Les résultats obtenus sur les sujets étudiés (6 hommes et 5 femmes) ont été traités statistiquement et on a montré qu'une extrapolation basée sur le poids corporel était possible pour des situations où les forces de support du bras ne sont pas connues. L'activité myoélectrique des muscles élévateurs du dos a également été analysée. L'objectif de cette étude était de fournir un outil d'analyse qui peut être utilisé dans tous les environnements du travail et qui permet une évaluation de l'astreinte lombaire pour la position assise avec un minimum d'équipement complexe. Un exemple d'application est présenté.

Eine Analyse der Belastung der Lendenwirbelsäule in sitzender Haltung wurde für die Fälle, Arme auf dem Arbeitstisch ganz oder teilweise abgestützt, durchgeführt. Es wird eine Methode zur biomechanischen Abschätzung der auf die Bandscheiben im Lendenbereich ausgeübten Momente und Druckkräfte vorgestellt. Dazu wird eine Kraftmeßplatte, eine Fernsehkamera und ein integriertes System zur genauen Erfassung der Signale eingesetzt. Das mit diesem Meßaufbau online erzeugte Bild zeigt den resultierenden Vektor überlagert mit dem Bild der menschlichen Gestalt und gestattet eine differenzierte Analyse der intervertebralen Belastung. Die Ergebnisse der Untersuchung an 6 Männern und 5 Frauen wurden statistisch ausgewertet und es wurde gezeigt, daß eine Extrapolation auf der Grundlage des Körpergewichts möglich ist, wenn die Armkräfte unbekannt sind. Die myoelektrische Aktivität der Stützmuskulatur wurde ebenso erfaßt. Das Ziel dieser Studie war es, ein Instrumentarium, das bei allen beruflichen Bedingungen angewendet werden kann, zu entwickeln, das die Abschätzung der Belastung der Lendenwirbelsäule bei geringstmöglichem Meßaufwand erlaubt. Ein praktisches Anwendungsbeispiel dieses Konzeptes wird vorgestellt.

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