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# RELATIVE MECHANICAL LOAD ON BACK AND HIP MUSCLES IN STANDING POSITION WHEN HANDLING MATERIALS MANUALLY

## *A Study of Packing Work*

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**ABSTRACT. Muscular load on the back and hip muscles was quantified and compared using a muscular strength utilization ratio (MUR). The MUR was obtained by dividing the total moment about the bilateral joint axis by the counteracting maximum muscular strength at the same joint angle. 72 different postures during simulated packing work were studied, with different combinations of box size, angle, edge height and weight. The MUR was calculated for a large, an average sized and a small man depending on whether they were all either strong, of average strength, or weak, thus giving nine MUR values for each posture. For a weak man, the MUR exceeded 100 % in many postures. The largest box at a zero- or 30-degree angle to the horizontal with its upper edge 20 cm below elbow height gave the highest MUR, while the smallest box angled at 90 degrees with the upper edge 10 cm above elbow height gave the lowest. The presented concept of relating joint load to strength is proposed for use in preventive ergonomic counselling and in vocational rehabilitation.**

*Key words:* biological models, biomechanics, ergonomics, hip joint, joint load, rehabilitation, work posture.

There is considerable evidence for a relationship between low back pain and work load (2), and the association of hip disorders with low back pain has been mentioned (13, 26). Both Thurston (26) and Murray (17) found a changed movement pattern of the lumbar spine and pelvis during gait in patients with osteoarthrosis of the hip.

Many studies concern the mechanical stress on the low back during work, but few focus on the hip (19). The present study concerns the relationship between the load on the hip and that on the low back during standing manual materials handling. We have found no studies investigating the load on the hip and back simultaneously.

The bilateral back extensors are usually weaker than the bilateral hip extensors (3, 4, 20, 24, 27). This diminishes the value of direct comparison between the load moment on the back and and the load moment about the hip joint axes. And as shown in Fig. 1 *a* the magnitude of back extensor strength varies considerably at different joint angles. Fig. 1 *a* is a review, from the literature, of the isometric maximum strength at different joint angles for the back extensors (9, 22, 23, 28). Muscular strength is here expressed as the maximum voluntary moment of force about the joint axis and is measured in Newton metres (Nm). Although there is a large variation in absolute strength magnitude between different populations, the general shape of the strength curves is similar. They show lower back-extensor strength at extended and neutral joint angles and higher strength at flexed joint angles. To show this more clearly, in Fig. 1 *b* the same curves were normalized to 100% at the top value of each curve (9, 22, 23, 28).

Fig. 2 *a* reviews the hip extension curves for one leg (8, 18, 21, 29). The curves follow the same general pattern as for the back with lower extension strength at neutral position and higher strength at more flexed joint angles. In Fig. 2 *b* the curves for the hip were normalized to 100% at the top value of each curve (8, 18, 21, 29). For one leg only the absolute magnitude of the hip extension strength is lower than for the bilateral back extension strength, but if the strength for both hips is combined the hip extension strength becomes considerably higher than the back extension strength.

Thus the main difficulties of direct comparison of different load moment values are that the strength differs from one joint to another and at different joint angles. This can be resolved in the following way: if the load moment about a joint axis is divided by the counteracting maximum muscular moment at the same joint angle, a ratio is created. It is here called the muscular strength utilization ratio (MUR)

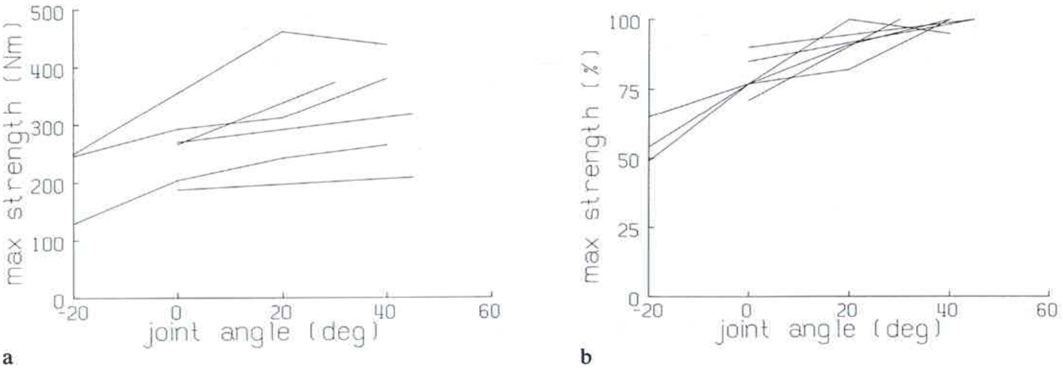

*Fig. 1.* Compilation of results from different investigations concerning isometric back extension strength at various joint angles found in the literature (9, 22, 23, 28). Zero is neutral position (*a*) Strength values in Newton metres. (*b*) Strength at top value of each material is here denoted 100%. Strengths at the other joint angles are given as a percentage of this joint angle.

(12, 25) and tells what percentage of an individual's maximum strength is required to assume a certain work posture. The load moment in Newton metres shows the stress or demand on the joint. Assessing this in relation to the maximum strength of the counteracting muscle group, which represents the capacity, gives a measure of the strain, the MUR. This ratio will also give a better understanding of what a given load moment about a joint really means for an individual worker.

The occupational health unit of a large manufacturing company in Stockholm was of the opinion that packing work caused considerable pain from the locomotor system. Therefore in the present investigation it was decided to investigate the load on the back and hip during packing work. The general aim was to analyse how various work-site conditions influenced the absolute and relative loads on the back and hip during standing packing work when handling objects of light to moderate weight. As far as we know, no other investigation of the biomechanical load on the back or hip during packing work has been undertaken so far. The following specific questions were analysed:

1. How much of the maximum muscular strength capacity in the back and hip is utilized in the packing postures?
2. What packing work posture gives the highest relative load on the back and on the hip?

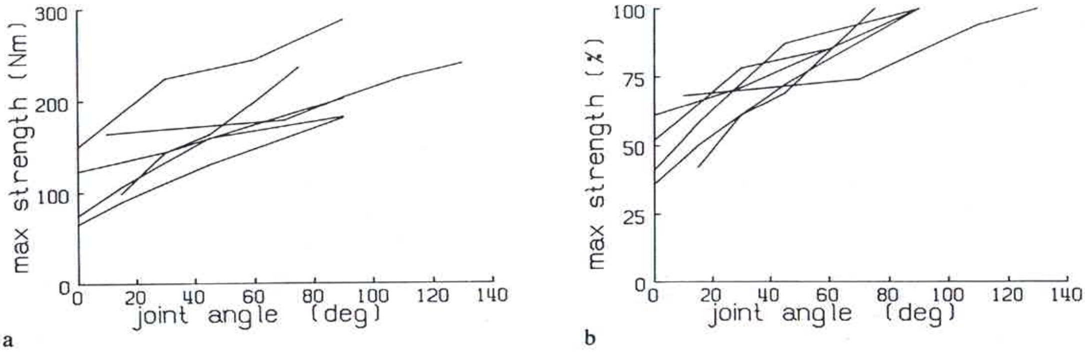

*Fig. 2.* Compilation of results from different investigations of isometric hip extension strength at various joint angles found in the literature (8, 18, 21, 29). Zero degrees is neutral position (*a*) Strength values in Newton metres. (*b*) Strength at top value of each material is here denoted 100%. Strengths at the other joint angles are given as a percentage of this joint angle.

Table I. *Anthropometric characteristics of the subjects*

In brackets: percentiles compared to 874 male conscripts aged 17–26 (15)

| | Large man | Average-sized man | Small man |
|---|---|---|---|
| Age (years) | 28 | 23 | 34 |
| Height (cm) | 197 (99) | 179 (55) | 164 (3) |
| Weight (kg) | 89.0 (99) | 69.0 (58) | 59.5 (21) |
| Height above floor (cm) | | | |
| Shoulder | 159 (98) | 145.5 (52) | 135.5 (8) |
| Head of radius | 124.5 (93) | 114.5 (58) | 103.5 (5) |
| Finger tip (dig III) | 75 (96) | 69.5 (69) | 63 (16) |

3. What packing posture gives the lowest relative load on the back and on the hip?
4. How does a change in the weight of the object handled influence the magnitude of the load moments?
5. What general conclusions can be drawn concerning the optimum size of the box to be packed, the height of its upper edge, the angle of the box and the weight of the object handled?

## MATERIALS AND METHODS

### *Subjects*

The subjects were three healthy male volunteers. None suffered from pain or disorders of the musculoskeletal system. One subject was close to average height and weight for Swedish conscripts (15). One was considerably taller and heavier than average, and one was considerably smaller. Some anthropometric characteristics are shown in Table I. For comparison the percentiles compared to 874 Swedish male conscripts between 17 and 26 years are shown in brackets (15).

### *Postures investigated*

In an introductory field study, the packing work at the central warehouse of a large manufacturing company in Stockholm (Ericsson) was studied. The packing procedures were recorded on photographs and video. Later, an adjustable work-station was built in our laboratory (Fig. 3). The influence of the following variables was studied:

1. Box dimensions: 59 cm length by 40 cm width by 21 cm depth (denoted 21), 61 cm length by 50 cm width by 34 cm depth (denoted 34) and 101 cm length by 67 cm width by 50 cm depth (denoted 50).
2. Angle between box and table surface of zero, 30, 60 and 90 degrees.
3. Upper edge of box: at elbow height for each individual; at 10 cm above elbow height, and at 20 cm below elbow height. This vertical distance was measured between the box edge closest to the subject and his elbow when his arms were hanging down by his side.
4. Weight of object carried: three kg or 10 kg.

This gave 72 different packing postures. In a pilot study, some of these were simulated by a healthy 1.89-m-tall male weighting 71 kg (12). Both the instant when the worker's hands passed the edge of the box and the instant just before the object was placed on the bottom of the box were studied. The phase that imposed the highest load on the body was always the latter (12). We have therefore concentrated on this phase in the present study.

The packing postures were simulated by the three subjects. The sequence was randomized for each subject. He was told to hold the object with both hands, just above a red cross in the middle of the bottom of the box, in a body position that he experienced as the most comfortable.

The postures were photographed perpendicularly to the sagittal plane. The distance from the subject to the camera was 4.0 m. A plumb-line with reference distance points was placed near the subject in the focal plane. Surface markers were attached to the skin of the subject over the ankle, knee, hip, shoulder, elbow and wrist. Markers were also placed over the spinous process of the seventh cervical vertebra, the first thoracic, the fifth lumbar and the first sacral vertebrae. To make it possible to see the location of the elbow and the object carried, the end of the box facing the camera was removed as indicated in Fig. 3.

### *Load moment calculations*

The photographs were placed on a semiautomatic coordinate registration table (Tektronix digitizer, 4953). The digitizer recorded the coordinates of the plumb-line with the reference distance points and the positions of the bilateral motion axes of the major joints. The digitizer was connected to a graphics teminal (Tektronix 4012) which was connected to a Nord-100 computer.

A multiple-link sagittal plane model based on static mechanics, which has been described elsewhere (11) was used with some modifications. The torso, head and neck, which were earlier treated as one single segment, were divided into two segments; one between the L5-S1 and C7-T1 spine motion segments and one between C7-T1 and the crown of the head.

The locations of the centres of mass relative to segment lengths were obtained using Dempster's (10) anthropometric data. The centre of mass for the head and neck segment was placed at the auditory meatus (10). Weights for each body segment were calculated in relation to body mass (10). All the load moments with respect to the investigated joint, including the moment caused by the object held in the hand, were added to give the total load moment.

### *Location of the L5-S1 spine motion segment*

The literature concerning the position of the instantaneous axes of rotation of the lumbar spine has been reviewed by White and Panjabi (30). In a normal lumbar disc, the instantaneous axes of rotation in the sagittal plane are found in a relatively concentrated area. When flexion is simulated starting from a neutral position, the axis lies in the region of the anterior portion of the disc. For extension, the axes are located at the posterior portion of the disc (30).

Using a sagittal section of a cadaver from a 50-year-old man (14), the posterior portion of the vertebral body can be located at 31% of the distance from the back to the abdomen, and the anterior portion at 44% of the same distance.

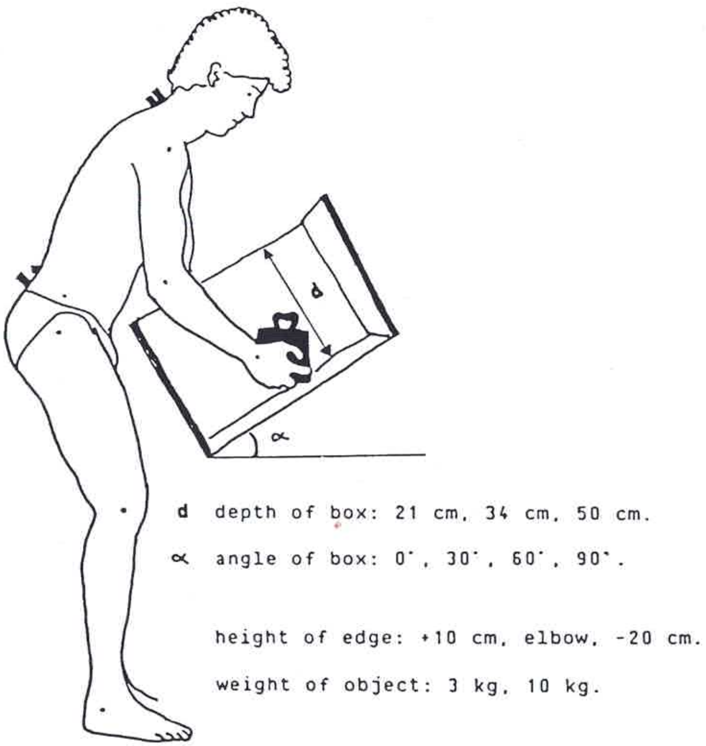

*Fig. 3.* Positions of subject and box. The box side facing the camera was removed. The variables are indicated.

To increase accuracy when marking the position of the L5-S1 spine motion segment using anatomical landmarks only, our calculations of the load moments about the bilateral L5-S1 axes of the subjects have been made about an axis placed midway between these points i.e. at 37.5% of the distance from the back to the abdomen.

*Location of the C7-T1 spine motion segment*

According to Lysell (16), the axes of sagittal rotation are located in the anterior portion of the subadjacent vertebra. On a sagittal section of a cadaver from a 41-year-old man, the anterior portion of the vertebral body was located at 58% of the distance from the posterior to the anterior border of the neck in the sagittal plane (14). The torso link in the present study was drawn to an axis placed at this point.

*Joint angle calculations*

The computer program used for calculating the load moments and joint angles gives separate load moments about the hip and L5-S1 axes, but only the combined angle between thigh and trunk. To separate the thigh-trunk angle into hip and L5-S1 joint angles, the following assumptions have been made. The amount of forward pelvic rotation relative to lumbar flexion is dependent on the amount of trunk flexion. From Dempster's (10) empirical data, this motion has been described by Chaffin and Andersson (7). The pelvis does not significantly rotate for the first 27 degrees of forward flexion.

During this part of the movement, most of the change in thigh-trunk angle can be attributed to the L5-S1 jont. Thereafter the pelvis contributes to the motion by rotating at the rate of 2 degrees for each 3 degrees of torso inclination. But if the thigh is inclined forward more than 10 to 15 degrees in relation to a vertical line, pelvic rotation is in the opposite direction to rotation of the L5-S1 motion segment, at the rate of 1 degree (pelvic) for each 3 degrees (thigh). If the trunk and thigh are inclined forwards simultaneously, the L5-S1 joint angle is the difference between the two contributing effects.

*Muscular strength utilization ratio (MUR)*

The load moment of force was used to compare the different packing postures. However, for reasons discussed earlier, the muscular strength utilization ratio concept (MUR) was also used. This is the quotient of load moment and counteracting maximum muscle strength at the investigated joint angle (12, 25).

The maximum muscular strength values for the hip were calculated from the joint moment-strength prediction equations presented by Chaffin and Andersson (7) which are based on data from Clarke et al. (8). For maximum strength about the L5-S1, the strength curves published by Smidt et al. (22) were used. The strength curves for both the hip and L5-S1 were adjusted to population strengths for males employed in manual work in industry. The population strength data was collected by Stobbe (24) and quoted in Chaffin and Andersson (7).

To facilitate general conclusions, the load moment obtained for the average-sized subject was divided by strength data for *a*) a man of mean strength (average load/mean

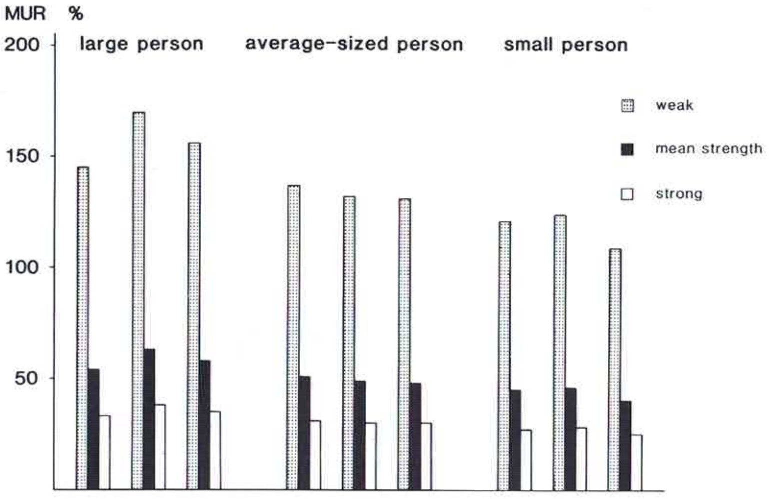

*Fig. 4.* Muscular strength utilization ratios (MUR) for the three work postures imposing highest load on L5-S1. From left to right in groups of three columns; the load for the large, the average-sized, and the small person. Black columns show MUR for a man of mean strength, stippled columns for a weak man at the 2.5th percentile and open columns for a strong man at the 97.5th percentile.

strength), *b*) for a very strong man at the 97.5th percentile (averaged load/great strength), and *c*) for a very weak man at the 2.5th percentile (average load/poor strength). The same analysis was made for the large man and the small man in the experiment. The final result was nine different MUR values for each packing work posture.

### *Reliability of load moment calculations*

To investigate the reliability of the load moment calculations, the whole experiment and calculation procedure was performed with one subject on three different occasions within a week.

## RESULTS

### *Reliability*

The three repetitions of the experiment with one of the subjects were statistically analysed using the Friedman two-way analysis of variance by ranks. Xr2 values of 0.11 were obtained for the hip and of 7.00 for the L5-S1. This means that no difference could be found between the three occasions for either the L5-S1 or the hip at the 99% level of significance.

### *Muscular strength utilization ratio (MUR)*

*Back muscles.* Fig. 4 shows the muscular strength utilization ratios (MUR) for the three work postures that imposed the highest load on the L5-S1 for the average-sized person. From left to right in groups of three columns, the loads for the large person, average-sized person and small person in these postures are shown. The middle column for each posture (black) shows what the MUR would have been if the subject were of mean strength (i.e. the 50% level in the population) the left column (stippled) shows what it would have been if the subject's strength were at the level of the 2.5% weakest in the population and the right column (open) if the strength were at the 97.5% level i.e. at the level of the 2.5% strongest in the population. The three work postures were the ones assumed with 1) the 50-centimetre box, 30-degree box angle, box edge at elbow height and 10 kilograms handled 2) the 50-centimetre box, 30-degree box angle, box edge at 20 centimetres below elbow height and 10 kilograms handled 3) the 50-centimetre box, 0-degree box angle, box edge at 20 centimetres below elbow height and 10 kilograms handled.

Fig. 4 shows the MUR values for the three postures that gave the highest load. In Fig. 5, which shows cumulative frequency polygons for the L5-S1 MUR values, it is possible to look up every MUR value for all 72 packing work postures. For example by looking at the MUR values (*x*-axis) for the 100th (72/72), 99th (71/72) and 97th (70/72) percentiles (*y*-axis) one gets the MUR values for the 3 postures that gave the highest load.

In addition, for every MUR value on the *x*-axis, the percentage of the investigated postures that received a lower or equal MUR is indicated on the *y*-axis. The steeper the line, the more observations were found in that particular *x*-axis interval.

For a man of mean strength (*m*), the MUR maximum varied between 46% (Small man) and 63% (Large man) depending on his size. For a man with strength at the 97.5% level in the population (*s*) the MUR maximum was between 28% (Small man) and 38% (Large man), and for a man who was at the

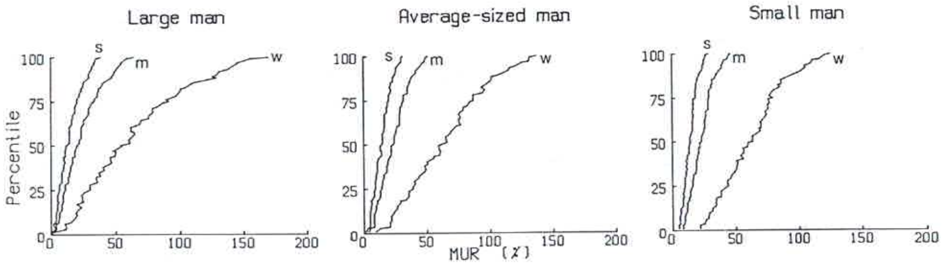

*Fig. 5.* Cumulative frequency polygons for muscular strength utilization ratios (MUR) at L5-S1 for all packing postures. *S*, strong man at 97.5th strength percentile: *m*, man of mean strength: *w*, weak man at 2.5th percentile. For every MUR value on horizontal axis the percentage that received a lower or equal MUR is indicated on vertical axis.

2.5% level (*w*) the maximum was between 124% (Small man) and 170% MUR (Large man). Note that the MUR value exceeded 100% for some postures. This means that the subject would not be able to assume this posture.

Most of the postures resulted in an MUR below 50% for a man of mean strength (*m*). A weak man (*w*) at the 2.5th percentile would only be able to assume between 80% and 90% of the postures, depending on his size.

Fig. 5 also shows that for the man of average size, 36, or half, the postures (50 on *y*-axis) resulted in an MUR of 14% or below if he were strong (*s*), of 23% or below if he were of mean strength (*m*) and of 62% or below if he were weak (*w*). The same patterns were obtained for the large man and the small man.

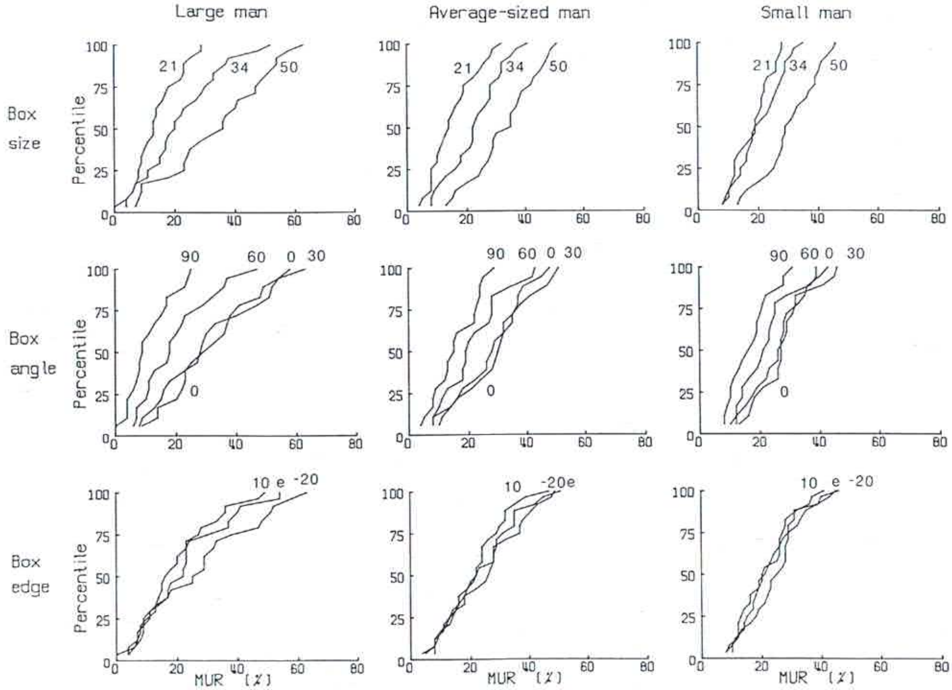

*Fig. 6.* Cumulative frequency polygons for muscular strength utilization ratos (MUR) at L5-S1 concerning variables investigated. Box depths 21, 34 and 50 cm. Box angled at 0, 30, 60 and 90 degrees to the horizontal. Box edge at elbow height (*e*), 20 cm below elbow height (−20), and 10 cm above elbow height (10).

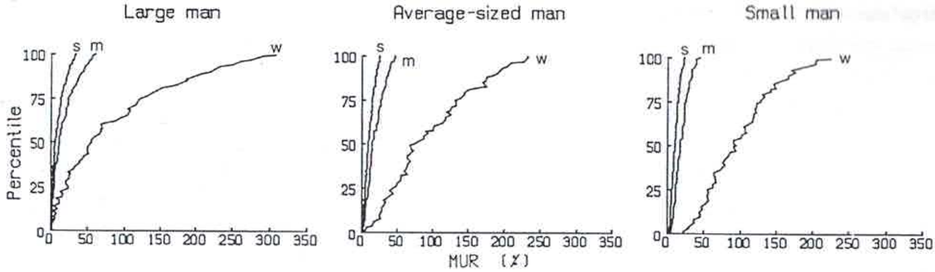

*Fig. 7.* Cumulative frequency polygons for muscular strength utilization ratios (MUR) at hip for all packing postures. *S*, strong man at 97.5th strength percentile; *m*, man of mean strength; *w*, weak man at 2.5th percentile. For every MUR value on horizontal axis the percentage that received a lower or equal MUR is indicated on vertical axis.

The curves for the strong small man (*s* in right diagram) and the weak large man (*w* in left diagram) indicate the possible range between the lowest and highest MUR values.

Fig. 6 illustrates the influence of box size (top), box angle (middle) and height of box edge (bottom) on the L5-S1 MUR value for a man of mean strength. The top diagrams show that the biggest box gave the highest load for all subjects while the smallest box gave the lowest load. The middle diagrams show that the zero- and 30-degree box angles resulted in the highest load, while the 90-degree angle gave the lowest load. The bottom diagrams indicate that the box edge at 20 cm below elbow height gave the highest load and that the box edge at 10 cm above elbow height gave the lowest.

*Hip muscles.* Fig. 7 shows the results for the hip. The number of postures a weak man would be able to assume was considerably less for the hip than for the back; between 53% (Small man) and 64% (Large man) depending on size. Half the postures (50 on y-axis) gave MUR values for the man of average size of 8% or below if he were strong (*s*), of 15% or below if he were of mean strength (*m*) and of 74% or below if he were weak (*w*). Consequently there was a higher relative load on the L5-S1 than on the hip for the average-sized man of high or mean strength. For the weak man the relative load was higher on the hip.

For both the hip and the L5-S1 segment, the posture with the highest absolute load (Newton metres) was ranked as number three according to relative load (MUR). For the average-sized man at the posture with the 50-cm box, 30-degree box angle and edge at elbow height, the load on the L5-S1, measured in Newton metres was 90% of the load on both hips added together. But in MUR the load for an average-sized man of mean strength was 51% for the L5-S1 and 46% for the hip. Note that for a weak person the load on the hip exceeded 300% in one case.

Fig. 8 illustrates the influence of box size (top), box angle (middle) and height of box edge (bottom) on the hip MUR value for a man of mean strength. The highest load was obtained with the largest box, the zero- and 30-degree box angles and the box edge at 20 centimetres below elbow height. The lowest load on the hip was obtained with the smallest box, the 90-degree box angle and the box edge at 10 centimetres above elbow height.

## DISCUSSION

As illustrated in Figs. 1*a* to 2*b*, maximum voluntary muscle strength varies with joint angle. Since our subjects adopted different joint angles for the various work postures, theoretically the MUR could differ considerably between postures, even with the same load moments. This is why it is important to take the joint angle into consideration, as the MUR does, and not only to focus on the load moment. It also explains why the postures imposing the highest load in Newton metres on the back and hip received only the third highest MUR.

A similar approach has been used by Chaffin and his colleagues (e.g. 1, 5). But these authors dealt mainly with maximum loads. In our terms this would be when the load exceeds 100% MUR. But since over-use injuries in contrast to overload injuries occur from repetitive exposure to submaximal limits, it is important to record and evaluate even the submaximal loads. Used and presented in our way, the MUR also becomes a tool for comparing different work postures to find the most favourable one. Hopefully it will also become possible to propose

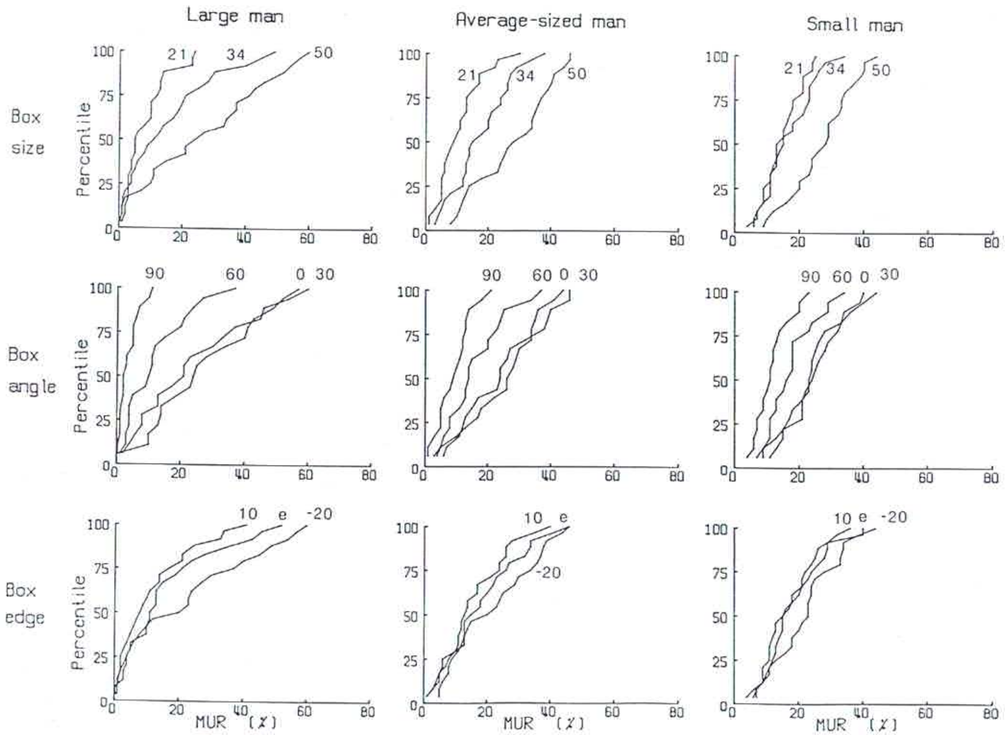

*Fig. 8.* Cumulative frequency polygons for muscular strength utilization ratios (MUR) at hip concerning variables investigated. Box depths 21, 34 and 50 cm. Box angled at 0, 30, 60 and 90 degrees to the horizontal. Box edge at elbow height (*e*), 20 cm below elbow height (−20), and 10 cm above elbow height (10).

maximum acceptable MUR limits, both for a single work posture and as a maximum allowed daily exposure. Given these maximum acceptable limits, preemployment strength testing (6) will become even more useful in primary prevention.

The multiple-link static sagittal plane model used in the present study follows the same principles as earlier models (e.g. 5, 11). The models used by Chaffin (5) and by Ekholm et al. (11) treat the torso, head and neck as one single link. In postures where the subject stretches his arms forwards in front of him (5) or flexes his neck (11), the link and consequently the centre of mass will be placed too far anteriorly, and will result in an overestimation of the moment arm and consequently the load moment. In the present model, the torso, head and neck form two segments; one between the L5-S1 and the C7-T1, and the crown of the head. In this way the position of the shoulder or head of the subject does not influence the estimated position of the centre of mass of the torso.

The maximum load moment about the L5-S1 segment in the present study was 76 percent of the maximum load when lifting 13 kg (11). For the hip, the figure was 83 percent (19).

The relative load (MUR) was somewhat higher for the L5-S1 than the hip, even though the absolute load (Newton metres) was higher for both hips added together than for the L5-S1. The explanation of this is that the hip extensor muscles about both hips together are much stronger than the back extensors.

Németh (19) has designed a diagram based on a theoretical biomechanical model for predictions of hip extensor muscular forces. Using this diagram we obtain in the present study a maximum hip joint load due to muscular forces of about 1 900 Newtons. By adding the gravitational force from the body segments above the hip we obtain a total compressive force of about 2 100 Newtons which is 3.1 times body weight. The 15 postures that gave the lowest load on the hip had a hip angle of extended position beyond neutral position. The diagram is not designed for these hip angles. The 16th posture had a hip angle of

6 degrees and resulted in a total compressive force of about one body weight. It makes sense that the hip angle was slightly beyond neutral position in the postures that resulted in the lowest load. In this way the subject moved his body centre of mass as close as possible to the hip and lumbosacral joints and thus minimized the moment arms.

Biomechanical models of the L5-S1 motion segment during lifting activities have been constructed by for example Gracovetsky et al. (13) and Anderson et al. (1). According to these models, disc compression increases as the trunk is flexed forward and disc pressure is highest at trunk flexion angles of 50 to 60 degrees. In the present study 11 of the 15 postures with the highest MUR values for the man of average size had trunk angles of 50 degrees or more, while all the postures which received the low MUR values had trunk angles of 6 degrees or less.

If one intends to avoid the highest relative load on muscle groups for both the back and the hip, it seems that packing postures which will result in a high thigh-trunk angle should be avoided (i.e. postures with a forward flexed trunk). As shown in Figs. 1*a* to 2*b*, the muscular strength for the back and hip is high at these joint angles, but apparently not high enough to compensate for the high load moments obtained. This leads to high MUR values in these joint angles.

The packing work postures which gave high MUR values were postures adopted when a large box was used and positioned horizontally or at 30 degrees to the horizontal, and with its upper edge below elbow height. In other words the load on the back and hip was not lowered by tilting the box from zero to 30 degrees. It had to be angled even more to result in a load reduction.

The packing postures which gave a low relative load on the low back and hip muscles were those that involved a zero or slightly extended thigh-trunk angle. Even though, as shown in Figs. 1*a* to 2*b*, the back and hip extensor strength is lower at these joint angles than at forward-flexed angles, the MUR was kept low because of the low load moment. The postures with a small box (21 cm depth) and the upper edge at 10 centimetres above elbow height gave the lowest MUR. A 90-degree angle to the horizontal gave the lowest load, but if a 90-degree box angle is impossible to arrange, the 60-degree box angle also gave lower MUR values than the 0-and 30-degree angles.

The presented concept of relating joint load to strength may give a better understanding of how high loads the workers in industry actually are exposed to. It may be helpful in preventive ergonomic counselling and in vocational rehabilitation.

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