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RELATIVE MECHANICAL LOAD ON SHOULDER AND ELBOW MUSCLES IN STANDING POSITION WHEN HANDLING MATERIALS MANUALLY

A Study of Packing Work

Ola K. Svensson,[1] Ulf P. Arborelius[1] and Jan Ekholm[2]

From the Kinesiology Research Group, [1]Department of Anatomy and [2]Department of Physical Medicine and Rehabilitation, Karolinska Institute, Stockholm, Sweden

ABSTRACT. When a patient with a musculoskeletal disorder returns to work after rehabilitation, the work-station should be designed so that the impaired muscle groups are less exposed to load. The work posture desirable for a particular muscle group might impose higher load on another muscle group. Since the shoulder muscles usually are stronger than the elbow muscles, a direct comparison of the loads is difficult. To make comparisons possible, the load moment about the investigated joints were divided by the counteracting maximum muscular moments, and a Muscular strength Utilization Ratio (MUR) was obtained. Using this principle, the muscular load on the shoulder and elbow was investigated in 72 different packing work postures. Different combinations of box size, box angle, edge height and weight of object handled were studied. There was a higher relative load on the shoulder than on the elbow. The concept of relating joint load to strength may serve as a guideline for how high a patient's strength should be before returning to work to avoid further injuries.

Key words: biological models, biomechanics, elbow joint, ergonomics, joint load, rehabilitation, shoulder joint, work posture.

Several studies indicate a relationship between mechanical load during work and shoulder pain (19, 21, 44). This supports the view that for optimum rehabilitation of over-use injuries to the shoulder, the work station should be designed so that the load on the shoulder is kept at a low level. Also, knowing the magnitude of the required work load will help the rehabilitation team to decide what capacity the patient should have before returning to work if new injuries are to be avoided. But a work posture which is favourable for the shoulder in terms of load might result in a high load on the elbow. In the present study, therefore, the load moments of force about both the shoulder and the elbow have been investigated. The load moment is the product of the load in Newtons and the moment arm or lever in metres.

The shoulder flexors are usually stronger than the elbow flexors (4, 7, 33, 39, 42). This diminishes the value of direct comparison between the load moment about the shoulder joint axis and the load moment about the elbow joint axis. And as shown in Fig. 1*a* the magnitude of the shoulder flexors varies considerably at different joint angles. Fig. 1*a* is based on a review from the literature of the isometric maximum shoulder flexor strength at different joint angles (8, 12, 32, 45, 46, 47). Muscular strength is here expressed as the maximum voluntary moment of force about the joint axis and is measured in Newton metres (Nm). Despite large variation in absolute strength magnitude between different populations, the general shape of the strength curves is similar. The shoulder flexors are stronger at extended joint angles and angles close to neutral position than 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 (8, 12, 32, 45, 46, 47).

Fig. 2*a* reviews the elbow flexion strength curves (1, 12, 14, 17, 18, 22, 23, 27, 29, 35, 38, 45, 46). Their general shape is a little different from the curves for the shoulder. For elbow flexion, maximum strength is at about 90 degrees joint angle, with minimum values at both ends of the motion range. This is perhaps clearer from Fig. 2*b*, where the elbow flexion curves have been normalized by denoting the top value of each curve 100% (1, 12, 14, 15, 17, 18, 22, 23, 24, 27, 29, 34, 35, 36, 38, 43, 45, 46). The location of the strength peak differs somewhat between investigations. This might be due to inconsistency in the techniques used, such as different subject positions or inability to maintain the exact joint angles desired while exerting the force. For two-joint muscles for instance, it is important to immobilize the adjacent joints.

Thus the main obstacle to direct comparison of

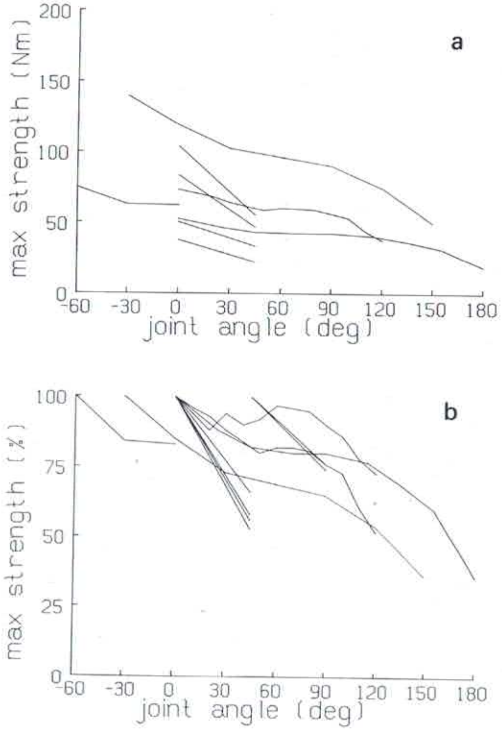

Fig. 1. Compilation of results from investigations concerning isometric shoulder flexion strength at various joint angles found in the literature (8, 12, 32, 45, 46, 47). Neutral position: 0 degrees. (*a*) Strength values in Newton metres. (*b*) Strength at top value of each material is here denoted 100%. Strengths at the other joint angles are given as a percentage of this joint angle.

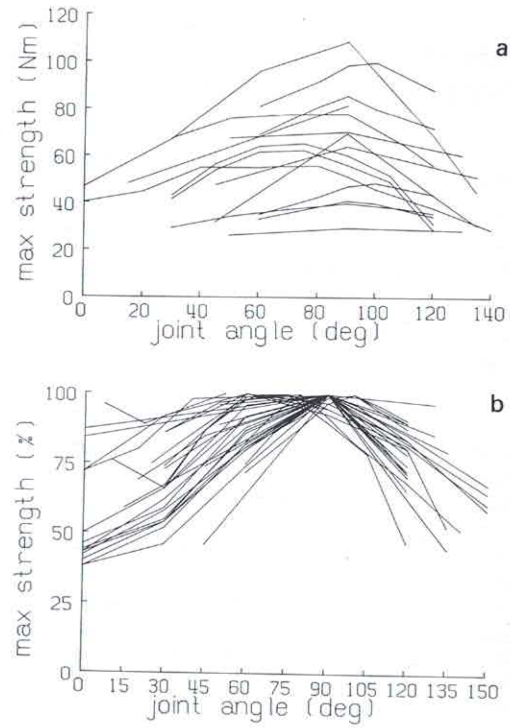

Fig. 2. Compilation of results from investigations of isometric elbow flexion strength at various joint angles found in the literature. Neutral position: 0 degrees. (*a*) Strength values in Newton metres (1, 12, 14, 17, 18, 22, 23, 27, 29, 35, 38, 45, 46). (*b*) Strength at top value of each material is here denoted 100%. Strengths at the other joint angles are given as a percentage of this joint angle (1, 12, 14, 15, 17, 18, 22, 23, 24, 27, 29, 34, 35, 36, 38, 43, 45, 46).

different load moments in absolute values is that strength differs from joint to joint and from joint angle to joint angle. If, however, the load moment about a joint axis is divided by the counteracting maximum muscular moment for the same joint angle, a ratio is obtained, here called the muscular strength utilization ratio (MUR) (16, 40). The MUR expresses what percentage of an individual's maximum strength the load in a certain work posture represents, thus giving an instrument for comparing load moments about different joints and at different joint angles.

Ergonomic injuries are defined as harmful effects of load attributable to workload factors (6). Occupations in packing and materials handling had 13.5 reported ergonomic injuries per 1000 employed in Sweden in 1980, and of these injuries 22% concerned the shoulder and arm (6). For this reason, it was considered important to investigate the load on the shoulder and elbow during packing work. In the present study the effect of different variables such as the size of the box packed, the angle of the box and its height relative to the elbow were studied. The knowledge gained should help in finding optimum packing work postures. It may also be applicable to prevention, and to rehabilitation of others doing similar work, such as assembly line and construction workers, shop assistants and auto mechanics.

As far as we know, no other investigation of the biomechanical load on the shoulder or the elbow during packing work has been undertaken so far. The following specific questions were analysed:

1. How much of the maximum muscular strength capacity of the shoulder flexors and of the elbow

flexors is utilized in the packing work postures?
2. What packing work posture gives the highest relative load on the shoulder and on the elbow?
3. What packing work posture gives the lowest relative load on the shoulder and on the elbow?
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 optimum box size, height of upper box edge, box angle and weight of object handled?

MATERIALS AND METHODS

2.1. *Subjects*

The subjects were three healthy male volunteers. None suffered from pain or disorders of the musculoskeletal system. One was close to average height and weight for Swedish conscripts (30). 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 parentheses (30).

2.2. *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: 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: 3 kg or 10 kg.

Table I. *Anthropometric characteristics of the subjects*

In parentheses percentiles compared to 874 Swedish male conscripts age 17–26 (30)

	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)

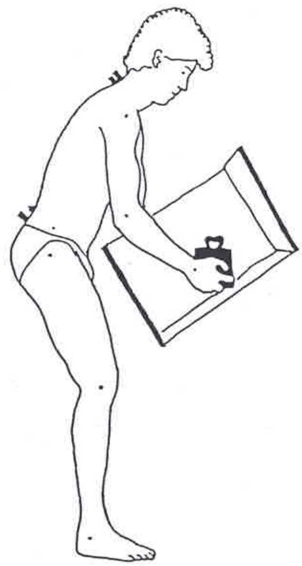

Fig. 3. Position of subject and box. The box side facing the camera was removed.

This gave 72 different packing postures. In a pilot study some of the postures were simulated by a healthy, 1.89 m tall male weighing 71 kg (16). 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 (16). We have therefore concentrated on this phase in the present study.

The packing postures were simulated by the three subjects. For each subject the sequence was randomized. 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 over the subject's shoulder, elbow and wrist. Markers were also placed over the spinous process of the seventh cervical and the first thoracic vertebrae. To expose the location of the elbow and the object carried, the end of the box facing the camera was removed as indicated in Fig. 3.

2.3. *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

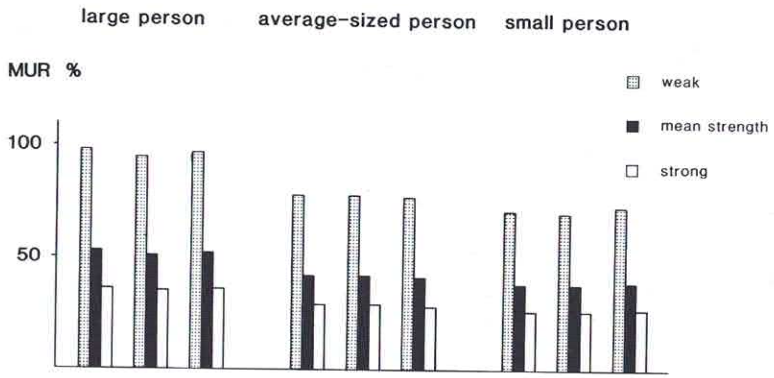

Fig. 4. Muscular strength utilization ratios (MUR) for the three work postures imposing highest load on shoulder. Black columns show MUR for a man of mean strength, stippled columns for a weak man at the 2.5th percentile and open columns for a strong man at the 97.5th percentile.

bilateral motion axes of the major joints. The digitizer was connected to a graphics terminal (Tektronix 4012) which was connected to a Nord-100 computer.

A sagittal plane model based on static mechanics was used for calculating the load moments about the bilateral shoulder and elbow axes (3). In this model the locations of the centres of mass relative to segment lengths were obtained using Dempster's (13) anthropometric data. Weights for each body segment were calculated in relation to body mass (13). 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. It was assumed that the load of the object was shared by both arms, 1.5 kg or 5.0 kg on each arm.

2.4. *Location of the C7-T1 spine motion segment*

According to Lysell (31), in the sagittal plane the axes of rotation are located in the anterior portion of the subadjacent vertebra. Using a sagittal section of a cadaver from a 41-year-old man (28), the anterior portion of the vertebral body can be located at 58% of the distance from the posterior to the anterior border of the neck. To increase accuracy when marking the position of the C7-T1 motion segment using anatomical landmarks only, our calculations of the load moments about the bilateral C7-T1 axes of the subjects have taken this point as the axis.

2.5. *Joint angle calculations*

The computer program used for calculating the load moments also gave the shoulder and elbow joint angles for each packing work posture.

2.6. *Muscular strength utilization ratio (MUR)*

The load moment of force alone was used to compare the different packing postures. However, for reasons described 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 (16, 40).

The maximum muscular strength values for the shoulder and elbow were calculated from the joint moment-strength prediction equations presented by Chaffin & Andersson (11) which are based on data from Schanne (37) and Stobbe (39). The level of the strength curves was obtained from measurements made on American males employed in manual work in industry (39).

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

2.7. *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

3.1. *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. Xr^2 values of 2.80 were obtained for the shoulder and 2.17 for the elbow. This means that no difference at the 99% level of significance could be found between the three occasions for either the shoulder or the elbow.

3.2. *Muscular strength utilization ratio (MUR)*

3.2.1. *Shoulder muscles*. Fig. 4 shows the muscular strength utilization ratios (MUR) for the three work postures that imposed the highest relative load on the shoulder for the average-sized person. From left to right in groups of three columns, the loads for the large person, the average-sized person and the 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

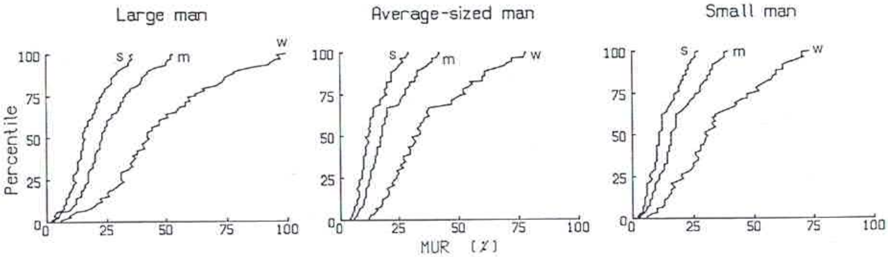

Fig. 5. Cumulative frequency polygons for muscular strength utilization ratios (MUR) at shoulder for all packing postures. s = strong man at 97.5th percentile concerning strength, m = man of mean strength, w = weak man at 2.5th percentile. For every MUR value on horizontal axis, the percentage that received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

have been if the subject were at the level of the 2.5% weakest in the population and the right column (open) shows the MUR if the subject were at the 97.5% level, i.e. at the level of the 2.5% strongest in the population. The three work postures were those with 1) the 50 cm box, 90 degree box angle, box edge 10 cm above elbow height and 10 kg handled; 2) the 50 cm box, 60 degree box angle, box edge 10 cm above elbow height and 10 kg handled, and 3) the 50 cm box, 90 degree box angle, box edge 20 cm below elbow height and 10 kg 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 MUR values, it is possible to look up every MUR value for all 72 packing work postures. For example by looking up 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 three postures that gave the highest load. In addition, for every MUR value on the horizontal axis, the percentage of the investigated postures that received a

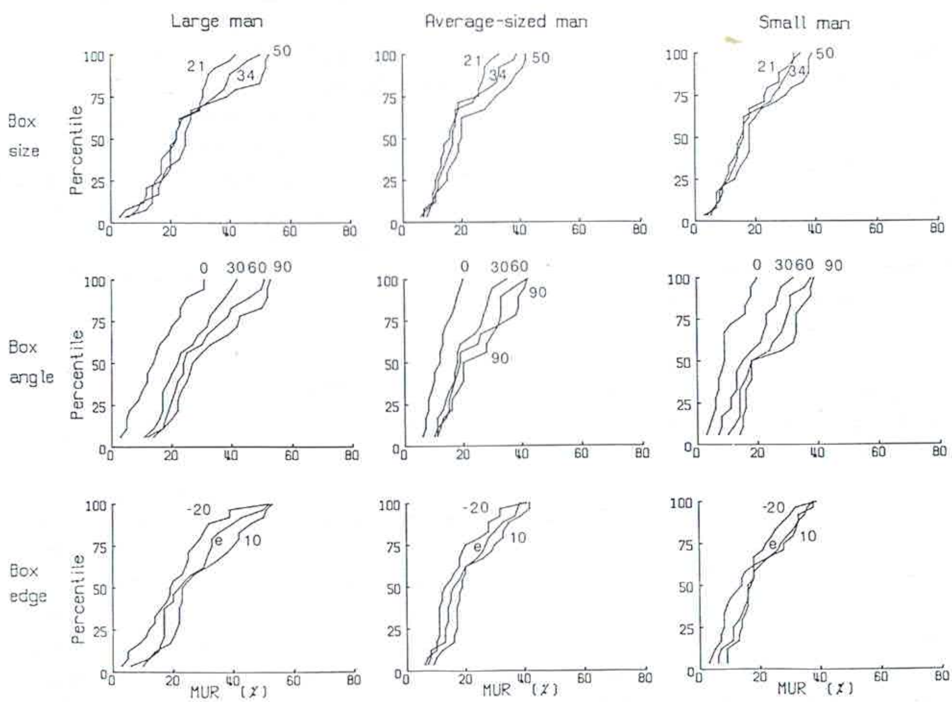

Fig. 6. Cumulative frequency polygons for muscular strength utilization ratios (MUR) at shoulder concerning variables investigated. Box depths 21, 34 and 50 cm. Box angled at 0, 30, 60 and 90 degrees. Box edge at elbow height (e), 20 cm below elbow height (−20), and 10 cm above elbow height (10).

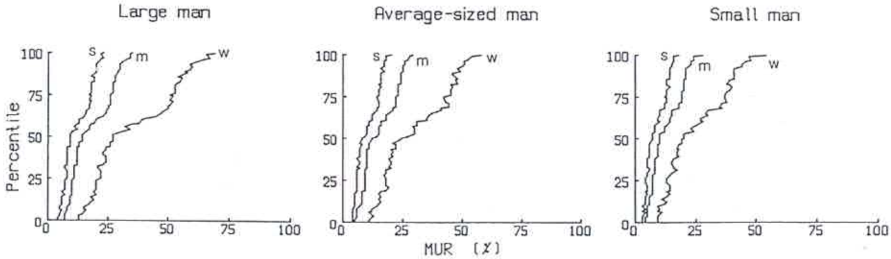

Fig. 7. Cumulative frequency polygons for muscular strength utilization ratios (MUR) at elbow for all packing postures. Otherwise as in Fig. 5.

lower or an equal MUR is indicated on the vertical axis. The steeper the line, the more observations were found in that particular *x*-axis interval.

For the man of mean strength (*m*), the MUR maximum varied between 39% (small man) and 53% (large man) depending on his size. For the strong man (*s*) the maximum was between 27% (small man) and 36% MUR (large man), and for the weak man (*w*) the maximum was between 73% (small man) and 99% MUR (large man).

For a man of mean strength (*m*), most of the postures resulted in an MUR below 50%. None gave an MUR above 100%, meaning that if the limitations were on this body region only, a man could assume all the postures investigated even if he were weak (*w*). For the man of average size, half the postures (50 on vertical axis) resulted in an MUR of 12% or below if he were strong (*s*), of 18% or below if he were of mean strength (*m*) and of 33% or below if he were weak (*w*). The same patterns were obtained for the large man and the small.

Fig. 6 illustrates the influence of box size, angle and edge height on the shoulder MUR value for a man of mean strength. The top three diagrams (size) show that the biggest box (50) gave the highest load for all subjects while the smallest box (21) gave the lowest load. The middle diagrams (angle) show that the 90 degree box angle resulted in the highest load, and that the 0 degree box angle gave the lowest load. The bottom diagrams (edge height) indicate that 10 cm above elbow height (10) gave the highest load and 20 cm below elbow height (−20) gave the lowest.

3.2.2. *Elbow muscles*. Fig. 7 shows the results for the elbow. All the postures resulted in an MUR of 35% or below for a man of mean strength (*m*). 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 12% or below if he were of mean strength (*m*) and of 24% or below if he were weak (*w*). Consequently there was a higher relative load on the shoulder than on the elbow. The posture with the highest relative load (MUR) at the elbow was ranked as number three in absolute value (Newton metres).

Fig. 8 illustrates the influence of box size (top), box angle (middle) and height of box edge (bottom) on the elbow MUR value for a man of mean strength. Here the differences in load patterns were less clear. The highest load was obtained with the largest box, and the box angles of 30-, 60-, or 90 degrees, while the values for all the different box heights were very similar to each other. The lowest load on the elbow was obtained with the two smallest boxes and the 0 degree angle. The most favourable box height was more difficult to determine. Finding the optimum work posture for the elbow gave a lower relative load reduction than for the shoulder.

DISCUSSION

In Figs. 5 and 7 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. In reality for healthy individuals the interval will probably be much narrower, since it is unlikely that a small man's strength is at the 97.5th percentile and that a large man's is at the 2.5th. However, for patients after a period of inactivity, muscular weakness is not unusual, even if the body dimensions are large. This means that some patients will be exposed to very high MUR values in some of the work pos-

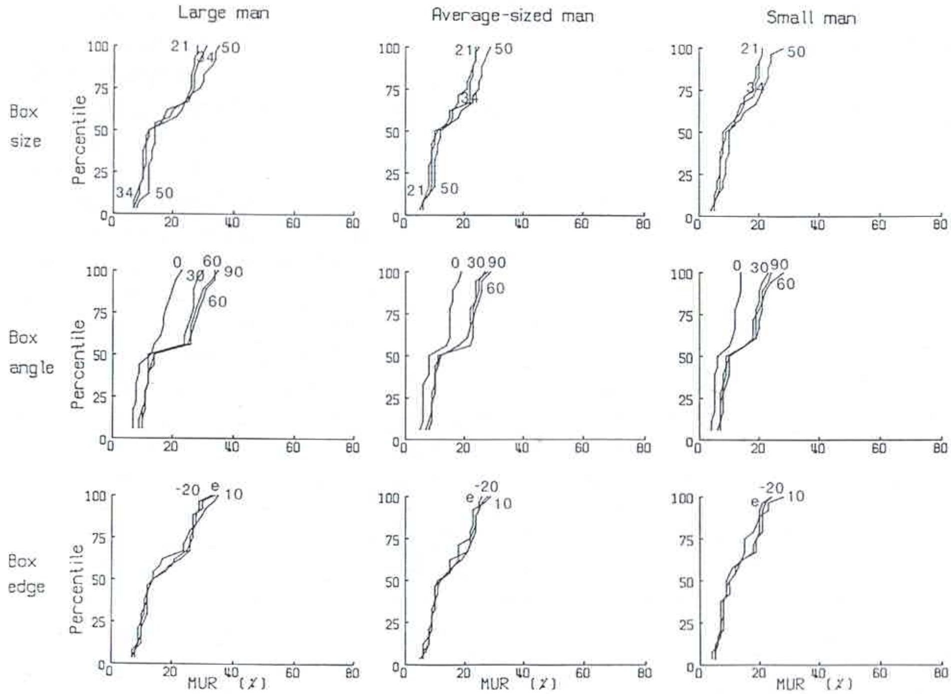

Fig. 8. Cumulative frequency polygons for muscular strength utilization ratios (MUR) at elbow concerning variables investigated. Otherwise as in Fig. 6.

tures. Using this reasoning, it will also be possible to propose guidelines for how high a patient's strength should be before returning to work if further injuries are to be avoided.

As shown in Figs. 1*a* and 1*b* shoulder flexion strength is greatest at a zero-degree joint angle or at even more extended joint angles. Figs. 2*a* and 2*b* show that elbow flexion strength is greatest at about a 90 degree joint angle. The theoretical optimum work posture from the muscular point of view is achieved at a joint angle where the quotient of external load moment and maximum voluntary strength is as low as possible. This is not necessarily at the joint angle where the person is strongest or the angle which gives the lowest external load. When the combination of both factors is optimized, the MUR will be at its lowest value. This explains why the posture with the highest relative load (MUR) at the elbow ranked only number three in Newton metres.

The variables that gave the highest MUR for the shoulder were the largest box angled at 90 degrees to the horizontal with the upper edge 10 centimetres above elbow height. This combination resulted in a shoulder angle of more than 65 degrees for all three subjects. At these shoulder angles the load moment will be fairly high, and since shoulder muscular strength decreases from neutral to flexed joint angles (Fig. 1*b*) this will result in a high muscular strength utilization ratio. Low MUR values were obtained with the smallest box angled at 0 degrees with its edge 20 cm below elbow height. This combination gave shoulder angles of around 20 degrees or less. At these angles the load moment in the numerator is lower, and the muscular strength in the denominator higher, than in high-MUR postures, thus resulting in a low quotient (MUR).

For the elbow, the relationship is more complex. The highest elbow load moment is obtained when the forearm is horizontal, because this results in the longest moment arms for the external load. The position of the forearm depends on both elbow angle and shoulder angle. An elbow angle of 90 degrees combined with a shoulder angle of 0 degrees gives the same load moment about the elbow as an elbow angle of 0 degrees together with a shoulder angle of 90 degrees. However, muscular strength is lower in the latter combination (Figs. 2*a* and 2*b*) so this will result in a higher MUR. The variables that gave the lowest MUR on the elbow was the two smallest boxes, the 0-degree angle and the box edge at either height.

The idea of taking both load moment and strength into account is not new. Chaffin and colleagues have used the same concept (10, 11). However, they focused on load maxima for single occasions. The intention was to give a basis for the avoidance of over-load injuries. But since over-use commonly results from repetitive exposure to submaximal limits, it is also important to record and evaluate the submaximum loads. Here the MUR concept provides a tool for establishing maximum acceptable exposures to submaximum loads, i.e. during a whole working day as well as for a single lift or packing event. The method may be used in field studies either alone or in combination with others such as VIRA (26) or the method used by Keyserling (25). In addition the MUR concept can be used to find ways of lifting or handling that give the least load on a specific body region. The MUR can thus become a valuable tool in advising patients with localized load-elicited pain.

As reported earlier (3) the maximum shoulder load moment when lifting a 13 kg box is 51 Newton metres. The maximum load moment in the present study was 37 Newton metres or 42% MUR, i.e. 14 Newton metres lower. The packing work posture which gave the lowest load with the 10 kg object resulted in only 9 Newton metres or 10% MUR. This shows how much could be gained by finding the optimum work posture. In another study (2) the maximum load imposed during machine milking with a 3 kg hand-held implement is about the same as in the posture with the maximum load during packing with a 3 kg object. The minimum load during packing was a third of this value.

In some of the postures with the box edge 10 cm above elbow height, the worker had to abduct the shoulder to reach above the edge of the box. This would result in an adducting and inward-rotating load moment in addition to the already-existing extending moment. However, the magnitude of this moment was not calculated in the present study. It would have to be counteracted by the abductors of the shoulder, e.g. the supraspinatus and the acromial portion of the deltoid (5, 9, 20). This movement is combined with upward rotation of the scapula (5, 9) caused by e.g. the serratus anterior and trapezius muscles. An inward-rotating moment about the gleno-humeral joint is balanced by the infraspinatus, the teres minor and the spinal portion of the deltoid (20). The maximum strength in performing outward rotation and abduction is lower than the maximum shoulder flexion strength (32). This will contribute to a higher strain on these shoulder muscles in the postures with abducted and inward rotated arm. It has also been suggested that the acromion impinges on the rotator cuff and may lacerate it during abduction in internal rotation (44). In the present study, standing very close to the box to reduce the extending load moment in the sagittal plane sometimes seemed to result in a higher degree of abduction and internal rotation of the shoulder. The postures with abducted and inward-rotated shoulder might also give an adducting load moment about the elbow, which might be harmful to patients with load-elicited pain in this region, e.g. associated with lateral epicondylitis.

In conclusion there was a higher relative load on the shoulder than on the elbow. Variables that gave the highest relative load (MUR) for the shoulder were: 1) the largest box 2) angled at 90 degrees to the horizontal (i.e. lying on its side), 3) and with the upper edge 10 centimetres above elbow height. For the elbow the variables were: 1) the largest box, 2) box angles of either 30, 60 or 90 degrees, and with 3) the box edge at either height. Packing work postures that gave the lowest relative load for the shoulder were obtained with 1) the smallest box size 2) angled at 0 degrees (i.e. with the opening upwards) and 3) with the box edge 20 cm below elbow height. For the elbow the lowest relative load was obtained with 1) the two smallest box sizes, 2) the 0 degree box angle, and with 3) the box edge at either height.

The concept of relating joint load to muscular strength may serve as a guideline. A person should have the necessary muscular strength in the muscle groups used in a particular work before he returns to work. In this way he might hopefully avoid further injuries.

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Address for offprints:

Dr Ola K. Svensson
Kinesiology Research Group
Department of Anatomy
Karolinska Institute
Box 60 400
S-104 01 Stockholm