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International Journal of Industrial Ergonomics 30 (2002) 103–113

International Journal of Industrial Ergonomics

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The effect of maximum voluntary contraction on endurance times for the shoulder girdle ☆

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Received 6 February 2001; received in revised form 11 January 2002; accepted 4 February 2002

Abstract

This study investigated endurance times as percentages of maximum voluntary contractions (MVCs) in 12 healthy females (mean 25.8 ± 4.3 years) in 5 postures and at 7% MVCs. The shoulder postures utilized were 30/90 (shoulder forward flexion = 30° and included elbow angle = 90°), 60/90, 90/120, 120/150, and 150/180. The %MVCs were 5%, 15%, 30%, 45%, 60%, 75%, and 90% of MVC at each of these postures. Outcome measures included: endurance times, ratings of perceived exertion, fatigue ratings, pain ratings, and surface electromyography (trapezius and mid-deltoid). As expected the endurance time decreased non-linearly with an increase in %MVC. However, the relationship between endurance time and %MVC differed significantly from Rohmert's curve and suggests it considerably overestimates endurance times for %MVCs $<45\%$ and it underestimates endurance times for %MVCs $>45\%$. This study's curve did not become asymptotic even at 5% MVC. Shoulder posture (shoulder forward flexion angle) had a significant effect on endurance time. In general, endurance time decreased with an increase in shoulder flexion angle up to 120° and then it increased. Thus, overhead work (hands above the head) would appear to be better designed with a greater degree of forward flexion, rather than in front of the worker at lower degrees of forward flexion.

Relevance to industry

Published data on endurance times for the shoulder girdle are scant, yet shoulder injuries are neither rare nor inexpensive. This study completely redefines the relationship between endurance time and %MVC for the shoulder girdle. It will allow for a better definition of worker capabilities for the design of overhead work.

Keywords: Endurance; Shoulder; Shoulder girdle; Rohmert's curve; Ergonomics; Electromyography

1. Introduction

Rohmert (1973a, b) and Rohmert et al. (1986) published data and graphs on the effects of endurance time as a function of maximum voluntary contraction (MVC). The "Rohmert's curve" has subsequently been widely cited as a guideline for the design of work. A common

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☆These results were presented, in part, at the Fourteenth Triennial Congress of the International Ergonomics Association, San Diego, CA, July 31, 2000.

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interpretation of those data has been that below approximately 15–20% of MVC, an individual is able to sustain that exertion indefinitely.

However, recent studies by Sjogaard et al. (1986), Nag (1991), and Rose et al. (1992) have drawn these data and conclusions into question. Generally, these studies have found that the Rohmert's curve overestimated the duration of exertion at low percentages of the MVC.

2. Objectives

The objectives of this study were to (1) evaluate the endurance times based upon the percentage of MVC and shoulder flexion angle in the female shoulder girdle and (2) assess these data in comparison with those predicted by the Rohmert's curve.

3. Materials and methods

3.1. Subjects

Twelve right-hand dominant, healthy, compensated female college subjects, ages 21–33 (25.8 ± 4.3 years) were enrolled in the study (See Table 1). Anthropometric measures, including height, shoulder height, body weight, upper arm length, lower arm length, hand length (wrist to center of grip), active range of motion, and grip strength were assessed. Two subjects had early symptoms of pain-free popping in the shoulder and were replaced. Subjects initially underwent a training phase for 3 weeks to ensure that subsequent activities were not unaccustomed.

During the study design budgetary and time constraints made it impossible to study both males and females, and maintain required sample size. Since in ergonomics the objective is to design jobs to accommodate as large a percentage of intended user population as feasible and females, in general, have lower physical capacity than males; it was decided to first study female subjects and to later study male subjects, if the resources became available.

Table 1
Subject demographics and anthropometrics

Variable	Mean ± S.D. (range)
Age (years)	25.8 ± 4.3 (21–33)
Height (cm)	168.4 ± 5.6 (159.0–176.8)
Shoulder height (cm)	136.9 ± 4.3 (127.5–143.3)
Weight (kg)	66.3 ± 10.8 (49.9–87.5)
Body mass index (kg/m^2)	23.5 ± 4.3 (16.5–33.0)
Upper arm length (cm)	34.8 ± 1.3 (33.3–35.8)
Lower arm length (cm)	26.2 ± 1.0 (24.9–28.2)
Hand length (cm)	5.8 ± 0.8 (5.1–7.1)
Shoulder active flexion range of motion (0° horizontal rotation and 180° elbow angle)	159.5 ± 11.9° (141.0–178.0)
Shoulder active flexion range of motion (0° horizontal rotation and 150° elbow angle)	159.1 ± 15.2°(133.0–186.0)
Shoulder active flexion range of motion (90° horizontal rotation and 180° elbow angle)	165.1 ± 15.7° (140.0–195.0)
Grip strength, pre-training (kg)	34.3 ± 5.1 (28.0–44.0)
Grip strength, post-training (kg)	34.1 ± 3.4 (29.3–40.3)

3.2. Materials

Subjects stood on a $1.3 \times 1.3\,\text{m}^2$ plastic platform and the position of the right great toe was marked. A manual goniometer was used to position the right upper extremity (dominant arm for all of the participatory subjects) prior to measurements. A suspended tennis ball was used for the subject to target each lift; she was instructed to lift the weight such that the bottom of the tennis ball was touched with the region of the distal dorsa of the second and third metacarpophalangeal joints. The posture was verified a second time prior to trials, as well as 3–4 times during trials with the goniometer. Advanced Orientation Systems tilt sensors (Model #EZ-Tilt 3000) were also used on the upper arm and wrist to verify posture within 2° throughout the protocol. The subjects were allowed to choose shoulder horizontal rotation for maximum comfort and most selected between 15° and 35°. Dumbbells with weight adjustments of 50 g increments were used. Response variables included endurance time, surface EMG and subjective ratings. Three different subjective ratings scales were used including: (1) ratings of perceived exertion for both the shoulder and, (2) elbow (Borg CR-10, Borg, 1982), (3) fatigue scale (0–10 scale with 0 = no fatigue and 10 = cannot continue any longer), and (4) pain scale (0–10 scale with 0 = no pain and 10 = worst possible pain) along with pain symptoms (Melzack, 1975). Software was written for this protocol and maintained on the data acquisition computer.

3.3. Postures and percentages of MVC

MVCs were determined with the subjects required to lift and hold the weight for 4 s (Chaffin, 1975; Sanchez and Grieve, 1992; Garg, 1983; Garg et al., 1980) without arching the back, raising the heels in a struggle to control the weight, shifting the weight or visible shaking. The shoulder postures studied were 30/90 (shoulder forward flexion = 30° and included elbow angle = 90°), 60/90, 90/120, 120/150, and 150/180. Results were replicated.

Endurance times were measured at 5%, 15%, 30%, 45%, 60%, 75%, and 90% of MVC for the five different shoulder postures. For those subjects whose active range of motion did not include the 150/180 posture, endurance time was determined at that subject's maximum active range of motion for 150/180. The endurance time was defined as the maximum amount of time a subject could continuously hold a given weight in a specified posture. Beyond this time a subject could not hold the weight no matter how hard she tried due to fatigue and/or pain in the shoulder girdle. The maximum limit on endurance time was set at 15 min.

Surface EMG, ratings of perceived exertion for both the shoulder and elbow (Borg CR-10 scale), fatigue and pain ratings for the shoulder girdle were recorded every minute at 5% of MVC, every 30 s at 15% and 30% of MVC, and every 10 s at 45% and 60% MVC, and almost continuously at 75% and 90% of MVC. In addition, baseline measurements were made at the beginning of the experiment (time zero). Measurements were also made just before a subject terminated an experiment. In nearly all cases subjects participated once per day. In very few instances ($<1\%$ of total experiments) subjects participated twice per day; once in the morning and once in the afternoon with a minimum of 6 h rest between the two sessions.

Endurance time experiments were part of a much larger study. All subjects had participated in these types of experiments for at least 2–3 months. They were very familiar with and trained in providing subjective ratings. Therefore, we were able to obtain the subjective ratings very rapidly at higher percent MVCs, where the endurance times were fairly short.

The measured endurance times were plotted and analyzed in two different ways. These were endurance times vs.: %MVC and %MVC adjusted for arm weight. Three different non-linear models (polynomial, power and exponential) were fitted to the endurance data that resulted in the smallest error sum of squares (curve fitting by least-square regression). Consistently, power and exponential functions resulted in higher r^2 values than polynomial functions. The r^2 for the 7 power and exponential functions were comparable (within ± 0.03). The power functions were finally selected to keep the relationships between endurance times and %MVC consistent.

Equivalent weights in the hand for arm weight via segmental body estimates (Clauser et al., 1969) were calculated by using an equivalent weight at the hand that would produce the same moment at the shoulder as the arm segment weights. This equivalent weight was added to the MVC to determine a new MVC called "MVC adjusted for arm weight." The same procedure was applied to submaximal weights (5%, 15%, 30%, 45%, 60%, 75%, and 90% MVC) to determine adjusted submaximal weights. The adjusted submaximal weights were divided by the MVC adjusted for arm weight to compute "%MVC adjusted for arm weight".

3.4. Surface electromyography

Surface EMG was monitored over the mid-deltoid and over the upper mid-trapezius. The myoelectric activity was recorded using amplified bi-polar, silver/silver-chloride, surface electrodes, 1 cm in diameter detection surfaces, spaced 2 cm apart on center. The electrode on the deltoid was placed (laterally rather than anterior or posterior) at a point halfway between the acromion process and the insertion of the deltoid on the deltoid tubercle. The electrode on the upper trapezius muscle was placed at the mid-point between the C7 spinous process and the posterior acromion process. The electrodes were grounded using a single Hewlett Packard Radio-Translucent silver/silver-chloride Monitoring Electrode (Part #M2202A), which was attached to the skin over the subjects olecranon process. The electrodes and ground were connected to a Therapeutics Unlimited (Model #544) electromyography monitoring system. Here, the EMG signals were further amplified and conditioned by a high pass filter set at 20 Hz. A computer using a 12-bit A/D data acquisition card sampled the signal at a rate of 1000 Hz per channel and digitally filtered the signal. A band-pass filter was set at 20–450 Hz with a 60 Hz notch filter to eliminate artifacts that would otherwise distort the EMG signal (60 Hz is the frequency of domestic alternating current electricity). This processed signal was stored in the data acquisition computer.

Root mean square (RMS) and median power frequency (MPF) analyses were performed on the signal in the time and frequency domains, respectively. For each combination of subject, posture and %MVC, the MPFs and RMS values at time zero were expressed as 100%. The MPFs and RMS values at subsequent times were normalized to the frequency and RMS values at time zero, respectively. The time for each experiment was also normalized and expressed as percentage of total endurance time. This was necessary because endurance times were different for different subjects, postures and %MVCs. With the normalized data, MPF vs. Time and RMS vs. Time could then be analyzed for all subjects.

3.5. Statistical analysis

Analysis of variance (ANOVA) (SPSS 9.0 for Windows) was performed to ascertain differences between %MVC and shoulder flexion angle. Paired *t*-tests were used to compare the surface EMG results.

4. Results

The raw data are graphed for endurance times for continuous holding of loads in five different shoulder postures and at seven different %MVCs in Fig. 1. For a given posture and %MVC there was large variability between subjects in endurance times. The coefficients of variation ranged between 21% and 43%.

As expected the endurance time deceased non-linearly with an increase in %MVC. As the %MVC is increased from 5% to higher percentages, the endurance time first decreased rapidly and then somewhat slowly (Fig. 1).

Shoulder posture (shoulder flexion angle) had a significant effect on endurance time. In general, endurance time decreased with an increase in shoulder flexion angle up to 120° and then it increased. In fact, endurance times were the largest for the 150/180 posture at 45%, 60%, 75% and 90% of MVC. For the %MVC $\leqslant 30\%$, endurance times for the 150/180 posture were the third largest. The 30/90 posture had the largest endurance times, followed by the 60/90 posture, for %MVCs $\leqslant 30\%$. In this regard, 10 subjects exceeded 15 min at 5% MVC and 1 subject at 15% MVC in the 30/90 posture, 2 subjects exceeded 15 min at 5% MVC in the 60/90 posture, while only 1 subject exceeded 15 min at 5% in the 120/150 and 150/180 postures.

In fitting the data to curves, the correlation coefficient (r^2) was 0.82 for the power function for the combined postures (range 0.79–0.91 for individual postures). The correlation coefficient was 0.86 using the exponential function for the combined postures (range 0.82–0.92 for individual postures).

An analysis of variance (5 postures × 7%MVCs × 12 subjects × 2 observations per cell) confirmed that both posture and %MVC had significant effects on endurance times ($p \leqslant 0.01$). Post hoc analysis showed that all %MVCs were significantly different from each other except: (1) the 45%MVC was not significantly different from the 60% MVC ($p > 0.05$), (2) the 60% MVC was not significantly different from either the 75% or the 90% MVC ($p > 0.05$), and (3) there was no difference between 75% MVC and 90% MVC

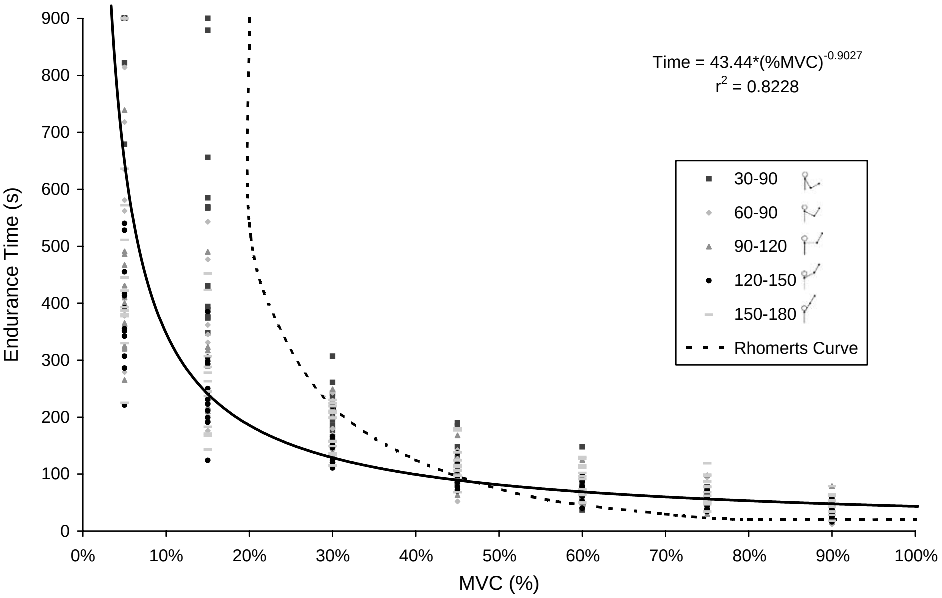

Fig. 1. Endurance time against %MVC for the five different shoulder postures and seven different %MVCs.

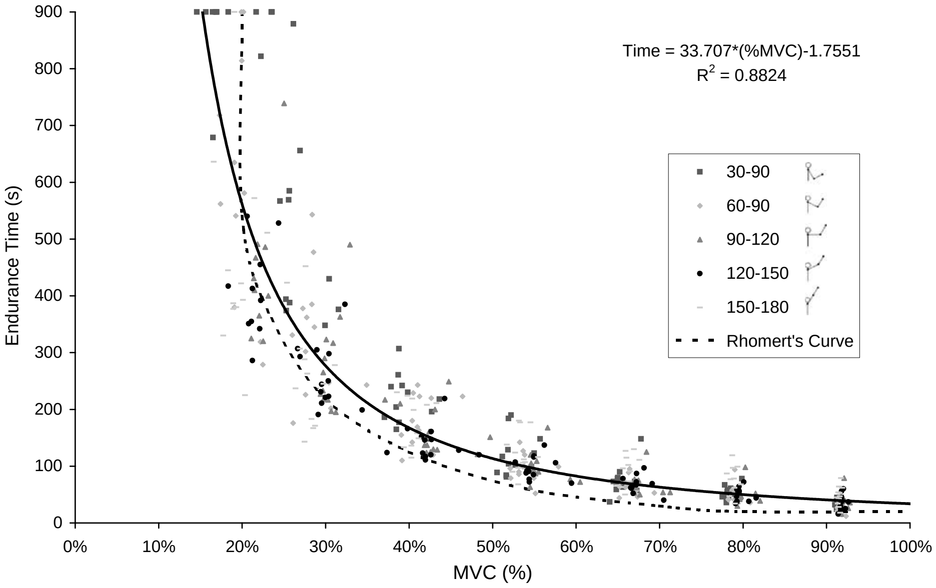

Fig. 2. Endurance time against %MVC adjusted for arm weight.

($p > 0.05$). Similarly, all postures were significantly different from each other ($p < 0.01$) except for the 90/120 and 120/150 postures.

A best-fit power function was fitted to the endurance data by adjusting both MVC and %MVC for arm weights (Fig. 2). The best-fit power function resulted in an r^2 of 0.88 as compared to 0.82 for the raw data.

In general, the MPF for the trapezius muscle decreased linearly with an increase in time (Fig. 3).

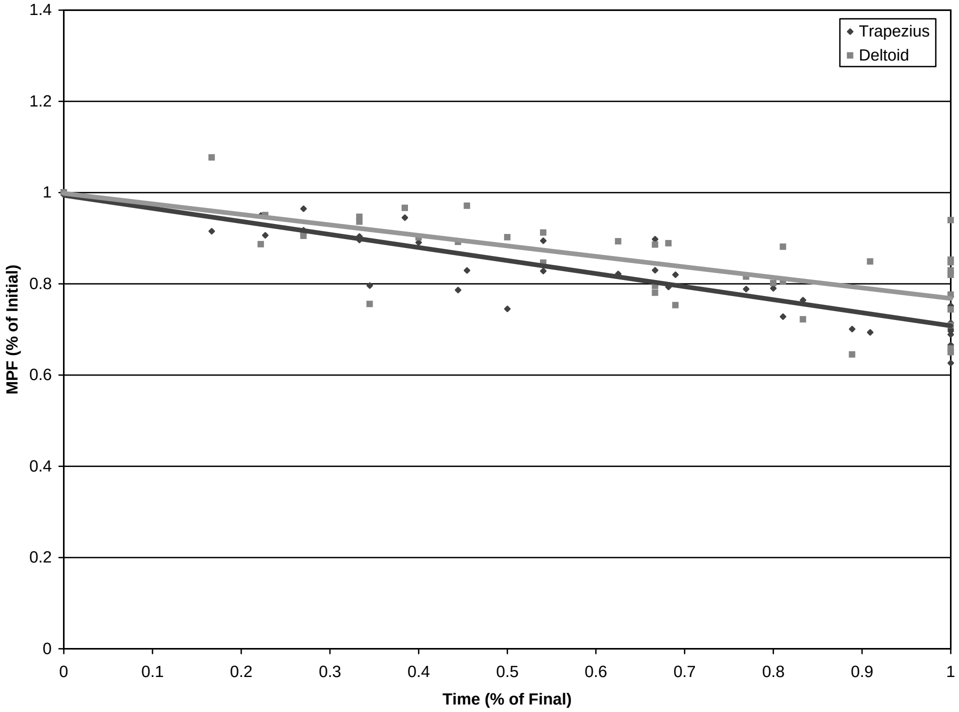

Fig. 3. Decrease in MPFs for trapezius and mid-deltiod muscles with time for 90% MVC at the 120/150 posture.

This was true for all %MVCs. On the other hand, the MPF for the deltoid decreased linearly with time for those %MVCs$\geqslant$30%. In spite of a linear decrease in normalized MPFs with time, there was large between subject variability in normalized MPFs at a given percentage of endurance time. Using paired *t*-tests for the trapezius muscle, normalized MPFs at the end of endurance time were significantly lower than the MPFs at the beginning of the experiment ($p \leqslant 0.01$) for all postures and %MVCs, with only one exception (5% MVC in the 30/90 posture). In general the MPFs for the deltoid muscle also showed significant decreases at 100% of endurance time for the 60/90, 90/120, 120/150, and 150/180 postures at %MVC $\geqslant$30.

In general, the RMS values for the trapezius at 100% of endurance time were not significantly higher than those at the beginning of the experiment ($p > 0.05$). Only 14 out of 35 posture and %MVC combinations were significant ($p \leqslant 0.05$), mostly for the 30/90 and 60/90 postures. On the other hand 21 out of 35 posture and %MVC combinations showed significant increases ($p \leqslant 0.05$) in the RMS values at 100% endurance time for the deltoid muscle. However, there was no systematic pattern for increase in the RMS value for the deltoid, neither for %MVCs nor for postures.

The ratings of perceived exertion (Borg CR-10 Scale) for the shoulder girdle and elbow joint and the ratings of fatigue and pain for the shoulder girdle were evaluated. For a given %MVC and posture, all the four ratings increased with an increase in exertion time. Fig. 4 shows the Borg CR-10 ratings for the shoulder for the seven %MVCs in the 90/120 posture. Among all four ratings, the ratings of perceived shoulder exertion were consistently the highest. In general, the ratings of perceived exertion for the shoulder were followed by shoulder fatigue ratings, then the ratings of perceived exertion for the elbow, and the shoulder pain ratings were the lowest.

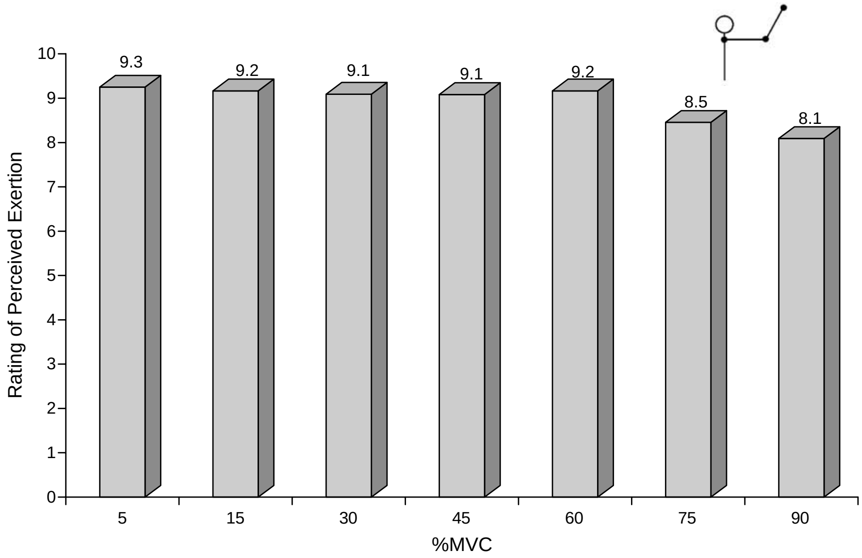

Fig. 4. Final ratings of perceived exertion (Borg CR-10) for the shoulder girdle at 100% of endurance times for the seven %MVCs at the 90/120 posture.

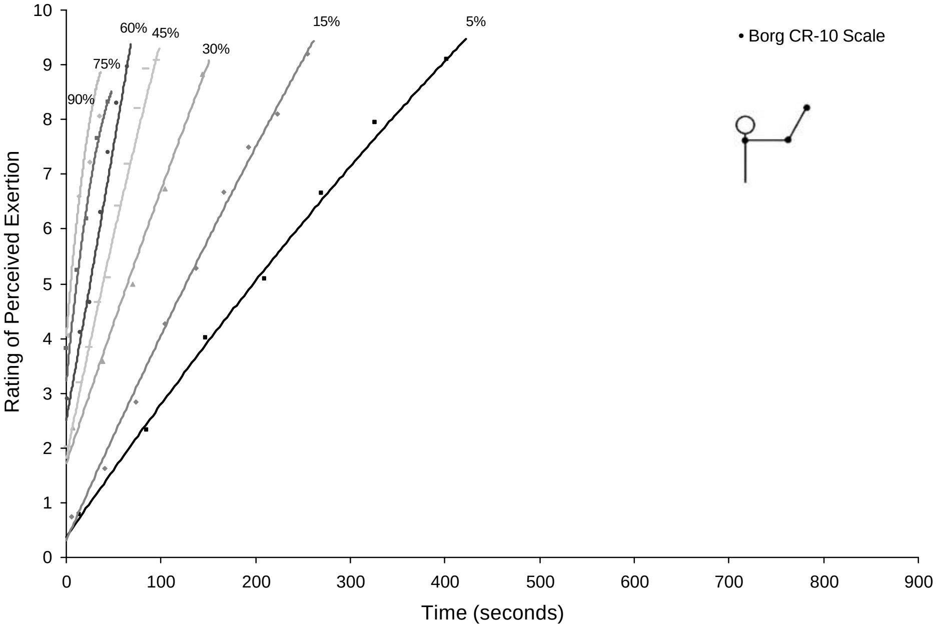

Fig. 5. Ratings of perceived exertion for the shoulder girdle vs. exertion time for posture 90/120.

Figs. 5–7 show time course plots for the Borg CR-10, fatigue and pain ratings for the shoulder girdle in the 90/120 posture. All three ratings increased with an increase in exertion time. As expected, the greater the %MVC, the greater the rate of increase in these ratings. Interestingly, all three ratings, at 100% of endurance time, were higher for low levels of exertion (for example, 5%

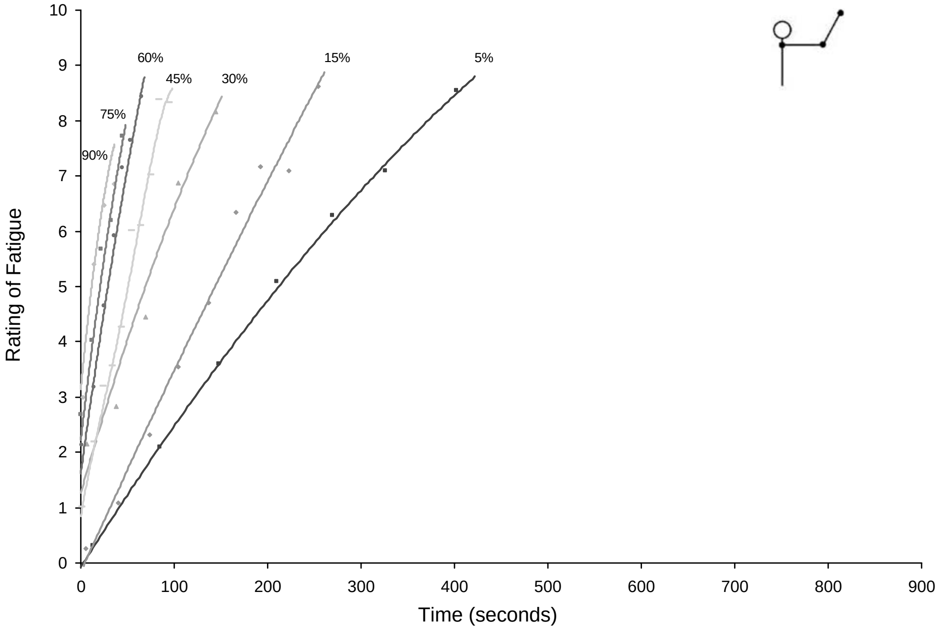

Fig. 6. Fatigue ratings for the shoulder girdle vs. exertion time for posture 90/120.

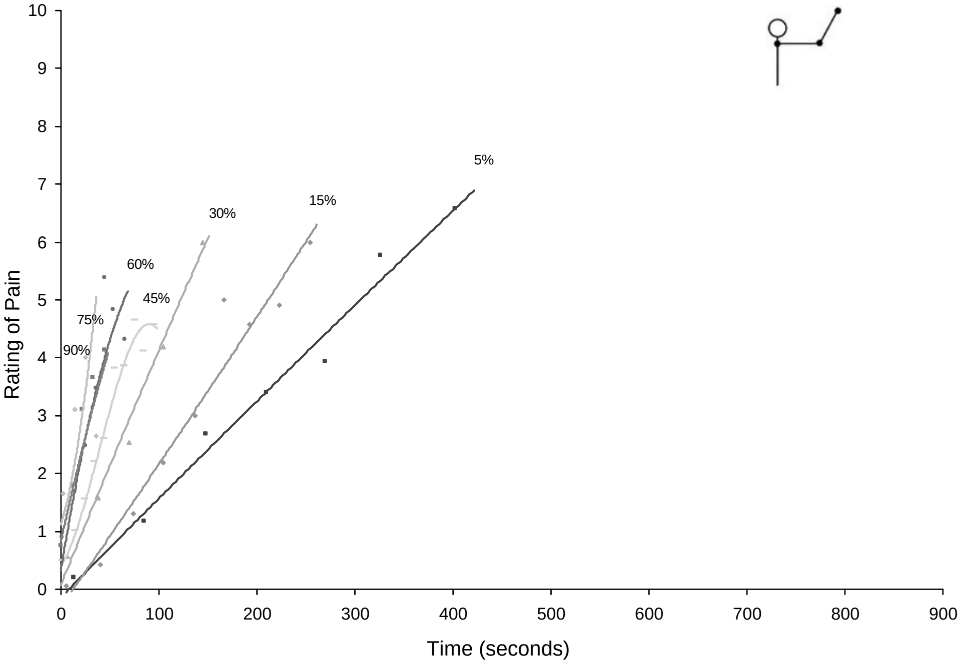

Fig. 7. Pain ratings for the shoulder girdle vs. exertion time for posture 90/120.

and 15% MVC) than at higher levels of exertion (for example, 75% and 90% MVC) (Figs. 5–7). For all practical purposes, at a given %MVC the Borg CR-10, fatigue and pain ratings increased almost linearly with an increase in exertion time (Figs. 5–7).

At 100% of endurance time, the subjects felt very high levels of exertion and fatigue in the shoulder girdle for all combinations of postures and %MVCs, with one exception (5% MVC at the 30/90 posture). The mean ratings of perceived exertion for the shoulder girdle ranged between 8.2 (more than "very hard") and 9.5 (almost "maximal") (Fig. 4). Similarly, the mean ratings of fatigue in the shoulder girdle ranged between 7.2 and 8.9 on a scale of 0 (no fatigue) to 10 (cannot continue any longer). All measures suggest these data represent valid measures of maximal durations of exertion.

The trends in these ratings over time were also evaluated. In general, the higher the %MVC, the greater the rate of increase in the perceived exertion rating with time for the shoulder girdle (Fig. 4). Thus, as expected, the perceived exertion level rose at a faster rate at higher %MVCs than at lower %MVCs. The fatigue ratings showed this same trend, but they peaked at lower levels than the ratings of perceived exertion. A similar trend occurred in the pain ratings, but they peaked at still lower levels of the maximal ratings. Also, the pain ratings at 100% of endurance time decreased with an increase in %MVC ($p \leqslant 0.01$). Thus, it was felt to be more painful (at the end of the experiment) to hold a lighter weight for a longer period of time than to hold a heavier weight for a shorter period of time. In other words, holding lighter weights to exhaustion is more painful than holding heavier weights to exhaustion. However, the heavier weights produce more pain than lighter weights when both are held for the same amount of time (such as 50 s).

5. Discussion

This study provides the most detailed published information on shoulder girdle endurance times as a percentage of MVC of which we are aware. These data from 5 postures (30°–150° of shoulder flexion) and 7 levels of %MVC (5–90%) would allow for the accurate assessment of endurance time as a %MVC for a wide range of postures and levels of %MVC via interpolation, particularly since the reported power and exponential functions have very high correlation coefficients ($r^2 = 0.79-0.92$).

The relationship between endurance time and the percentage of maximal exertion was one of the earliest as well as one of the most widely cited principles used for ergonomic job design. "Rohmert's curve" is basically a hyperbolic function of the relationship between endurance time and exertion as a percentage of the MVC. This study has again confirmed that this basic mathematical relationship is also accurate in the shoulder girdle.

Shown are the best-fit power function curve to the data ($r^2 = 0.82$) and the Rohmert's curve (Rohmert, 1962) in Fig. 1. The best-fit power function curve shows that: (1) there is a continuous non-linear decrease in endurance time with an increase in %MVC, (2) the endurance time decreases rapidly with an increase in %MVC up to about 30% MVC and then it decreases at a slower rate all the way up to 90% of MVC, and (3) the curve does not become asymptotic even at 5% of MVC. Graphs for individual postures were quite similar to that in Fig. 1.

One may argue that at low levels of exertion, some subjects may quit the experiment due to boredom and not due to physical fatigue. However, we did not find this to be the case, i.e., at low-level exertions, all our subjects quit due to physical fatigue and not due to boredom. First of all, we noticed that the subjects' arms were visually shaking towards the end of experiments, even at low levels of exertion. Secondly, as shown in Figs. 5–7 (1) all three ratings (Borg CR-10, fatigue and pain) increased with an increase in exertion time at low levels of exertion, (2) the final ratings were very high, (3) all three final ratings, at low levels of exertion, were greater than those at higher levels of exertion, and (4) for all practical purposes, the relationship between a rating and an exertion time remained linear at all levels of exertion. Lastly, as stated in the results, 10 subjects did exceed 15 min of exertion time at 5% MVC in the 30/90 posture, but they did not approach 15 min in any other posture at the same %MVC. This further supports our conclusion that the reason for quitting the experiments at low levels of exertion was physical fatigue and not boredom.

Other researchers have also reported that light workloads (smaller %MVCs) may cause either muscle fatigue or musculoskeletal complaints, especially in the shoulder, neck and lower back regions (Jorgensen et al., 1988; Sommerich et al., 1993; Veiersted, 1994; Aras, 1994; Rose et al., 1992; Sjogaard et al., 1986). For example, Rose (1992) reported endurance times of about 6–12 min at 5% MVC and 3.5–6.5 min at 15% MVC. Additional factors to consider included: how extreme the working situations were, extent of loading/unloading of the muscles during testing, and accustomed/unaccustomed tasks. Also, Dieen and Vrielink (1994) hypothesized that, among other variables, certain postures can result in lower endurance times even at the same relative load (%MVC) if those postures are thought to impede blood circulation through the musculature. This would be true for overhead work.

Since prior reports indicate that body segment weight can significantly affect endurance times depending on body posture and the muscle groups involved (Price, 1990; Rohmert et al., 1986; Rose et al., 1992), we included an analysis that adjusted the endurance for the body segment weight. On the other hand, Rohmert's endurance curve is applicable only in those situations where load due to body segment weight is negligible. However, unlike Rohmert's curve, the best-fit power function, even after adjusting for arm weight did not become asymptotic at a %MVC $\leqslant 20\%$.

This study's data suggest that the Rohmert's curve may not be an accurate estimate of endurance times for design of work vis-à-vis the shoulder girdle. Instead, the data provided in this article, particularly if confirmed by other investigators, provide more detailed endurance times for the design of work. Additionally, these data suggest that if overhead work were unable to be eliminated, it would be better to design such work to keep the hands close to the body to reduce moments on the shoulder joint. The endurance times for shoulder postures determined in this study confirm the above observation. For example the endurance times for 30/90 and 150/180 postures were significantly greater than those for the 90/120 and 120/150 postures. The first two postures would produce lower moments in the shoulder joint than the latter two postures.

Among the three subjective scales studied, the rating of perceived exertion (Borg CR-10 scale) consistently produced the highest ratings. It is unclear why the Borg CR-10 ratings were consistently higher than the fatigue ratings for the shoulder girdle. It would appear that perceived exertion ratings include more than fatigue. In this study, the subjects were able to differentiate between fatigue and pain. While the pain ratings were similar to fatigue ratings, they were consistently lower than fatigue ratings.

Between subjective and objective measures of fatigue, this study found that the subjective ratings were more informative than the objective measures. Both the perceived exertion and fatigue ratings showed how the fatigue was accumulating with time (Fig. 4). However, it was difficult to obtain similar information from surface EMG.

5.1. Limitations

The number of subjects was not large, though the variability in the subjects' strengths and endurances might well cover most of the range of typical female capabilities. Substantial variability is consistent with that reported by Jorgensen and Nicolaisen (1987), Dieen and Vrielink (1994) and Schultz (1972). These subjects were not self-selected into strength-requiring jobs. As such, there may likely be groups of female workers performing heavy materials handling tasks who may have significantly greater strength than this group of subjects. However, the relationship between endurance time and %MVC would also be expected to hold for those situations. While we incorporated a 3-week training phase, we cannot be sure that additional training time might not have increased the MVCs. Yet, the relationship between %MVC and endurance time would be expected to remain as reported in this study. The surface EMG was not helpful in the evaluation of fatigue as the Borg CR-10 scale was far more helpful. While the placement of the electrode over the anterior (rather than mid) deltoid segment along with utilization of needle EMGs might have been more helpful, it is believed unlikely that those changes would have surpassed the Borg CR-10 scale in sensitivity for fatigue.

6. Conclusions

The shoulder girdle endurance times from this study are significantly different from those reported by Rohmert (1964). The Rohmert's curve considerably overestimates endurance times for %MVCs $<45\%$ and it underestimates endurance times for %MVCs $>45\%$. Even at 5% MVC, subjects appear incapable of sustaining exertions indefinitely. Shoulder posture (shoulder forward flexion angle) has a significant effect on endurance time. In general, endurance time decreases with an increase in shoulder flexion angle up to 120° and then it increases. Tasks that need to be performed overhead appear to be better designed to be higher overhead (up to 150° of forward flexion) than at lesser degrees of forward flexion.

Acknowledgements

This study was partially funded by the American Automobile Manufacturers Association, Contract No. 9739-730 C 4.

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