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Electromyography (EMG) has been proposed as a method for determining muscle effort in repetitive upper limb tasks, which are often related to cumulative trauma disorders. EMG activity of the finger flexor musculature was investigated during a repetitive hand gripping task having 5 different cycle durations (2 to 6 s), various percentage of work time (and rest) within the work cycle (20% to 80%), and 3 different grip force levels. Thirty healthy adult participants each performed 27 randomly ordered 30-s repetitive hand gripping trials as well as 3 isometric contractions, which were used to normalize data from the hand gripping trials. There was a significant decrease in mean EMG as the duration of the work-rest cycle time increased. At each force level, EMG increased as the percentage of work time within the work-rest cycle increased, but to a greater extent at the highest force level. The results of this study suggest that overall muscle effort, and perhaps muscle fatigue, can be reduced most effectively by modifying the force requirements of the repetitive task. Other variables, such as the percentage of work time within a cycle and overall work cycle time have less effect on the EMG activity level. The results of this study have implications for developing strategies to reduce muscle fatigue during repetitive hand gripping tasks in an effort to reduce the effects of cumulative trauma disorders.

electromyography cumulative trauma disorders work-rest cycle
muscle force hand gripping

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1. INTRODUCTION

Sixty percent of all new work-related musculoskeletal disorders that are associated with repetitive trauma occur in the manufacturing sector (Bureau of Labor Statistics, 1995). Manufacturing jobs frequently characterized as highly repetitive and forceful increase risk of upper extremity cumulative trauma disorders (CTDs) such as tendonitis, tenosynovitis, and carpal tunnel syndrome. In a study by Silverstein and associates (1987), the prevalence of carpal tunnel syndrome was 0.6% among workers in low force-low repetition jobs but 5.6% in workers in high force-high repetition jobs. The growing use of high-speed assembly line techniques has increased the number of individuals exposed to highly repetitive, intensive hand activities and is thought to have contributed significantly to the increase of cumulative trauma disorders reported in many industries (Armstrong, Foulke, Joseph, & Goldstein, 1982; Barnhart, Demers, Miller, Longstreth, & Rosenstock, 1991; Chiang, Chen, Yu, & Ying-Chih, 1990; Feldman, Travers, Chiroco-Post, & Keyserling, 1987; Finkel, 1985; Punnett, Robins, Wegman, & Keyserling, 1985; Young et al., 1995). The elements of an upper extremity task, including forcefulness, repetitiveness, and work-rest characteristics, and the association of these elements with the development of muscular fatigue and repetitive motion disorders are matters of great interest to employers, employees, health and safety researchers, and health care providers.

Current algorithms used to derive appropriate contraction-relaxation or work-rest cycles are based primarily on studies by Rohmert (1973), Bjorksten and Jonsson (1977), and Dul, Douwes, and Smitt (1991). The work-rest curves that Rohmert (1973) reported have been referenced by other investigators and have been used by governmental and nongovernmental agencies to estimate rest allowances for both static and dynamic muscular work. Rohmert's work-rest curves, however, were based on data from only four healthy male participants performing intermittent static contractions of the biceps muscle using relatively long work times (minutes) with rest times expressed as a percentage of work time. Rohmert (1973) expressed the work levels performed by participants as a percentage of each individual's maximum voluntary contraction force but did not provide any indication of maximum force production in absolute terms.

Extrapolation of the classic Rohmert (1973) work-rest curves to the highly repetitive tasks associated with modern production lines may not be appropriate. It is questionable whether the classic work-rest data can be used to determine sustainable work-rest cycles for different muscle groups during a variety of both static and dynamic efforts. Other authors suggest possible overgeneralizations of the work-rest models that have been proposed previously (Mathiassen & Winkel, 1992). For example, Rohmert's data suggests that a static contraction requiring 15% or less of a maximum voluntary contraction can be sustained indefinitely. However, Bjorksten and Jonsson (1977) and Davenport (1990) have reported findings that indicate that this is not the case.

In many repetitive industrial tasks assembly line speed is set at a rate to achieve maximum productivity (Rodgers, 1987). For example, in meat processing plants it is not unusual for an employee to perform 12,000 or more cutting motions per 8-hr shift (Gjessing, Schoenborn, & Cohen, 1994). That equates to an average of 25 repetitions each minute with a work cycle time of 2.4 s. The variables that can be adjusted to reduce the adverse health effects associated with highly repetitive tasks include the force required by the task, the cycle time (or repetition rate), and the ratio of work to rest time within the cycle, also referred to as percentage of work time within the whole work cycle.

Surface electromyography (EMG) of a particular muscle group provides a means of estimating the relative contraction level or muscle effort. Surface EMG is affected by the number of motor units that are active within the detection area of electrodes and by the firing rate of those motor units (Lamb & Hobart, 1992). EMG has been shown to have a variety of occupational applications (Kadefors, 1978; Seroussi & Pope, 1987) and, within certain limits, has been used as a general estimate of muscle force during both static and dynamic work activities (Armstrong, Chaffin, & Foulke, 1979; Cook, Ludewig, Rosecrance, & Gerleman, in press; Silverstein, Fine, & Armstrong, 1986). During a highly repetitive work task, mean EMG over a given time period is likely to reflect both the muscle contraction force and the work-rest characteristics of the effort required to accomplish the task.

Unfortunately, there is a paucity of literature concerning EMG responses during highly repetitive work cycles, including repetitive hand gripping. The purpose of this study was to investigate the relationship between muscular contraction force, cycle time (repetition rate), or the percentage of work time within the work-rest cycle and mean finger flexor EMG activity during a highly repetitive hand gripping task. The results of the study may help to determine the contribution of these three factors to the overall muscle effort required to accomplish repetitive work tasks.

2. METHODS

2.1. Participants

Thirty healthy university students (8 male, 22 female) volunteered to participate in this study. The 30 participants in this study had a mean age of 25.8 yrs ($SD = 5.3$) with a range of 21 to 33 yrs. The participants' mean weight was 68.2 kg ($SD = 7.1$) and mean height was 171.7 cm ($SD = 6.1$ cm). Twenty-seven participants were right-handed and three were left-handed. Participants with current or prior injuries and illnesses to their hand or wrist were excluded. Methods and procedures were approved by the Institutional Human Subjects Review Board prior to data collection and all participants provided written informed consent prior to participation.

2.2. Instrumentation

Surface EMG from the forearm flexor musculature of the dominant arm was collected using bipolar silver-silver chloride electrode assemblies containing circuitry for on-site pre-amplification (Therapeutics Unlimited, Iowa City, IA). The electrodes provided on-site differential amplification with high input impedance (> 15 MΩ at 100 Hz) and a common mode rejection ratio of 87 dB at 60 Hz. The electrodes were connected to a differential main amplifier that provided an overall gain of 500 to 10,000 with a bandwidth of 40 Hz to 4 kHz (two-pole Butterworth filter). The raw EMG signal was sampled at a rate of 500 Hz and analyzed with a customized software program on a microcomputer that calculated the average RMS (root mean square) value for the digitized signal.

Three identical spring-loaded hand grip devices (Smith & Nephew, Germantown, WI) provided the resistance during the hand gripping task. The resistive forces for the three grip devices were 44, 67, and 133 N (10, 15, and 30 lb.). When a specific grip device was squeezed to the established range, a microswitch made contact providing current to a light-emitting-diode (LED) on a control panel positioned directly in front of the participant. Timed green and red lights on the control panel signaled the participant when to squeeze (green) and when to relax (red) during the repetitive task. A light was used rather than an auditory signal as most work-related activities are visually controlled. The LED allowed both the participant and the investigators to visually confirm that the hand grip device was being squeezed and released in accordance with the preselected work-rest cycle.

2.3. Procedures

Participants were seated comfortably in a chair with a back support and their dominant arm supported in 110–140° of elbow flexion and 0–10° of shoulder flexion. Goniometric measurements were used to assure that shoulder flexion and elbow flexion angles did not change throughout the period of data collection (approximately 1 hr). The literature suggests that participants normally self-select a wrist position that is optimal for grip strength during these types of repetitive tasks (O'Driscoll et al., 1992). Thus, the participants' wrist position was monitored by one of the investigators for any postural deviation. If a deviation was noted, the participant was reminded to return to the original position.

Placement of the EMG electrodes on the finger and wrist flexor musculature was determined using standard anatomical positions (Soderberg, 1992). The EMG surface electrode assembly was located on the medial forearm, one-fourth the distance from the medial epicondyle to the distal wrist crease. A reference electrode was placed on the participant's contralateral wrist.

The participants were assigned to a random sequence of 30 different gripping conditions (nine different work-rest cycles at the three force levels and an isometric condition at the three force levels). The cycle time of each task was defined in this study as the sum of the time in which the control panel lights indicated that the participant was to squeeze the spring-loaded device (work) plus the indicated time that the participant was to relax their grip (rest). These cycle times ranged from 2 to 6 s and were made up of nine selected combinations of work times and rest times as outlined in Table 1. The three force levels used in this study were submaximal and comparable to hand gripping forces often encountered with industrial production work (Cook, Ludewig, Rosecrance, & Gerleman, in press).

Pilot data indicated that there were no significant differences in mean RMS EMG values obtained during 30-s or 60-s data collection

TABLE 1. Mean RMS EMG (Newton Force-Equivalents) for Nine Work-Rest Combinations and Three Hand Grip Force Levels During Repetitive Hand Gripping (N = 30)

Work Time Within Cycle (%)	Work-Rest Ratio (s)	Cycle Time (s)	Hand Grip Condition 44 N	67 N	133 N
			Mean RMS EMG		
20	1–4	5	28.9	36.0	68.9
33	2–4	6	32.5	43.1	80.5
33	1–2	3	40.5	48.5	97.0
50	3–3	6	43.1	50.7	110.2
50	2–2	4	44.5	56.0	117.0
50	1–1	2	51.2	64.5	120.5
67	4–2	6	47.1	63.6	136.1
67	2–1	3	54.7	67.6	142.3
80	4–1	5	55.2	69.4	153.9

Notes. RMS—root mean square, EMG—electromyography.

periods. Therefore, to minimize the likelihood of a fatigue effect, data were sampled for 30 s under each work-rest combination. The 30-s sampling period allowed for a minimum of five work-rest cycles to be sampled for each trial. Isometric EMG was obtained during a 5-s contraction at each of the three force levels to calculate EMG force equivalents.

The participants were instructed to exert only enough force to close the microswitch and light the LED. When relaxing, the participant was instructed to relax as completely as possible without altering hand position. Participants performed several 30-s practice trials prior to initial data collection and were allowed 15 to 20 s rest and two to three practice cycles prior to each trial. Total testing time was approximately 1 hr for each participant. Six participants underwent the test procedures two weeks later to evaluate test-retest reliability.

2.4. Data Analysis

For each participant, the mean RMS EMG activity during each of the three isometric trials was used in a regression analysis to develop a force-EMG calibration. These individual calibration curves were used to convert the mean RMS EMG from each 30-s repetitive hand gripping trial into force-equivalent units (i.e., Newtons), allowing comparisons across participants (Armstrong, Chaffin, & Foulke, 1979).

An analysis of variance (ANOVA) was used to test for the main effects and interactions of force level, cycle time, and percentage of work time within the work cycle. At the highest force level, post-hoc Bonferroni-adjusted pairwise comparisons were used to examine the effect of cycle time within conditions having the same percentage of work time within cycle (i.e., 33%, 50%, and 67%). A multiple regression model was developed to examine the variability in the mean EMG that was explained by each of the three independent variables. Test-retest reliability was evaluated using an intraclass correlation coefficient. An alpha level of .05 was used as the criterion for significance in all statistical tests.

3. RESULTS

Representative instantaneous RMS EMG recordings from a typical participant for the nine combinations of work-rest conditions are depicted in Figure 1. There are four important features that can be observed in this typical record. Firstly, the response of the participant to the "work" signal was somewhat variable even though the task was repetitive and predictable. Secondly, there is a constant (electromechanical) delay between the onset of the EMG and the closure of the switch on the grip device. Thirdly, the participant many times, but not always, anticipated the repetitive signal by beginning muscular activation prior to the lighting of the work signal. And, finally, the amplitude of the EMG signal tends to be higher for the shorter contraction times, even though the force required to successfully activate the grip device was the same for all the conditions shown in this figure.

EMG data from the 30 participants was averaged for each of the 27 conditions and is presented in Table 1. As expected, the largest mean EMG values were recorded at the highest grip force level (133 N). Within a specific cycle time (i.e., 6 s), mean EMG increased as the percentage of work time increased at all three force levels (Table 1).

The results of the ANOVA indicated a significant main effect ($p < .0004$) of the cycle time of the hand gripping activity on RMS EMG (Table 2). As illustrated in Figure 2, shorter cycle times tended to have higher mean EMG values. There was a statistically significant interaction ($p < .0001$) between grip force and the percentage of work within the work cycle. At each force level, muscle activity increased as the percentage of work time within cycle increased, but the rate of increase

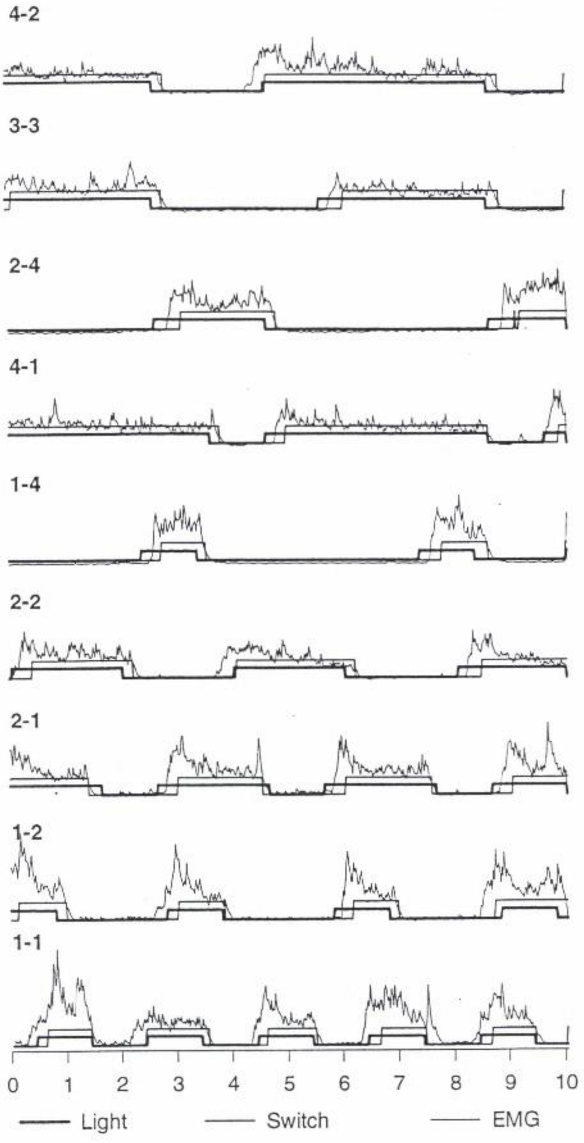

Figure 1. Sample recording from a representative participant for the nine combinations of work-rest used in this study. Each work-rest combination is indicated above and to the left of each tracing. Time in seconds is indicated along the abscissa. Thick lines indicate when the "work" light was on. Thin lines indicate closure of the grip device microswitch. Remaining trace is instantaneous root mean square (RMS) electromyography (EMG) from finger flexors.

was greater for higher force levels. This interaction effect is depicted graphically by the differences in slopes of the best fit lines through the EMG data as shown in Figure 3.

TABLE 2. Results of Analysis of Variance of Mean RMS EMG During Repetitive Hand Gripping Tasks

Source	*df*	*SS*	*F*-value	*Pr* > *F*
Force	2	37155	597.53	0.0001
Cycle Time	4	639	5.14	0.0004
% Work Within Cycle	3	8613	92.40	0.0001
Force * Cycle Time	8	38	0.16	0.9962
Force * % Work	6	2604	13.96	0.0001
Cycle Time * % Work	1	13	0.43	0.5133
Force * Cycle Time * % Work	2	16	0.26	0.7687
Error	756	23504	—	—

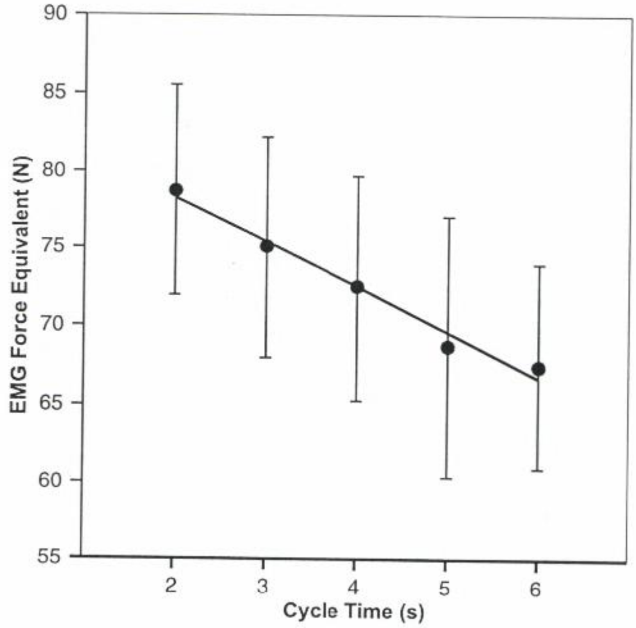

Figure 2. Mean electromyographic force equivalents (N) relative to cycle time (s) for all participants.

At the force of 133 N, Bonferroni-adjusted post-hoc analysis revealed nonsignificant changes in EMG activity due to cycle time within each of the percent work categories (33%, 50%, and 67%). The EMG force equivalent at the 3-s cycle time (1 s of work, 2 s of rest) was 17% greater than at the 6-s cycle time (2 s of work, 4 s of rest) and approached a level of statistical significance ($p = .013$). Because we were interested in all 5 post-hoc comparisons at the 133 N force level, the adjusted level of significance was $p < .01$ (0.05/5). The differences in EMG due to cycle

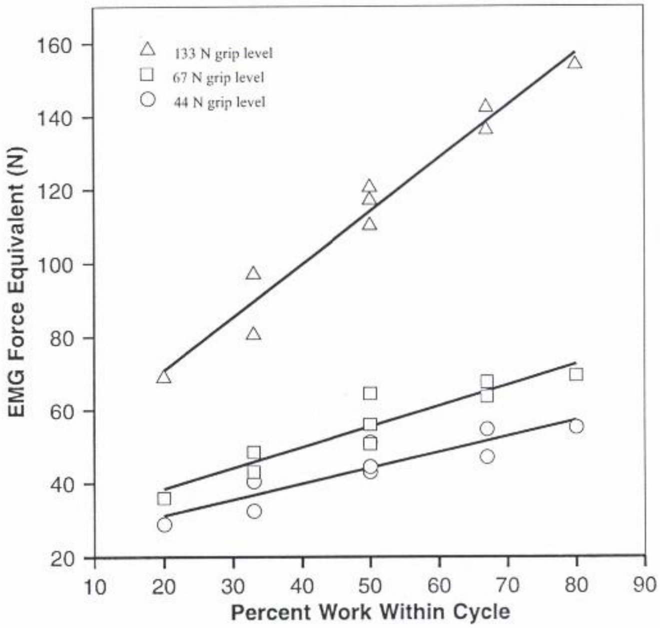

Figure 3. Mean electromyographic force equivalents (N) relative to the percentage of work time within cycle for three grip force levels for all participants. Regression lines are shown to clarify the electromyography (EMG)-percentage of work time relationship for each of the three grip force levels.

time at the 44 N and 67 N grip force levels were smaller in magnitude and also not statistically significant.

Multiple regression analysis for predicting EMG activity levels for our model included the variables of force, cycle time, and percentage of work time within the work cycle. This model resulted in an overall regression coefficient of $r^2 = .936$. Thus, 94% of the variability in this model was explained by these three variables. The partial r^2 values were .749 for force, $r^2 = .174$ for percentage of work time within the work cycle, and $r^2 = .013$ for cycle time. The regression equation for this model is Mean RMS EMG $= -22.55 - 2.769$ Force $+ 0.811$ Percent Work $+ 0.806$ Cycle Time. Units for EMG and force are Newton-equivalents and Newtons, respectively. The units for cycle time are seconds.

Test-retest reliability was performed on six participants two weeks following the initial testing. The intraclass correlation coefficient for test-retest reliability was .965 indicating that the findings were highly repeatable from week-to-week.

4. DISCUSSION

This study examined the effects of force, cycle time, and percentage of work time within the work cycle on mean finger flexor EMG activity during a repetitive hand gripping task. The results of the present study generally agree with Rohmert's thesis (1973) that force level and percentage of work time within cycle are critical determinants of muscle effort during tasks having relatively long cycle times. In regard to highly repetitive hand gripping activities that have relatively short cycle times, the results of the present study indicate that the effect of the absolute time of the work cycle on mean EMG, although statistically significant, is negligible compared to the effects of force and percentage of work time within the work cycle. This finding is also in agreement with the work of Rohmert (1973) and Rodgers (1987). It would appear that reductions in overall muscle effort can be accomplished to a greater extent by reducing the force requirements of the gripping task and shortening the percent of work time within the work cycle rather than altering the task cycle time (repetition rate).

Although the relationship between muscle use and musculoskeletal disorders has not been well established, workers performing tasks characterized by forceful, highly repetitive muscle exertions are more likely to develop musculoskeletal disorders (Armstrong, Fine, Goldstein, Lifshitz, & Silverstein, 1987; Armstrong, Foulke, Joseph, & Goldstein, 1982; Armstrong, Young, Seaton, Edwards, & Feely, 1992; Punnett, Robins, Wegman, & Keyserling, 1985; Silverstein, Fine, & Armstrong, 1987; Stock, 1991). Assuming that there is an association between muscle fatigue and cumulative trauma disorders, modifying elements of the task such as effort level and percentage of work time within the work cycle may assist in the reduction of muscle fatigue and musculoskeletal disorders. In the industrial setting, however, the manufacturing process may be difficult to modify or redesign. The cycle time and the force level needed to complete a task may be impractical to alter in some circumstances. The results of the present study suggest that if those two factors are fixed, EMG activity can be reduced, to some extent, by decreasing the percentage of the cycle during which muscles must contract, or, conversely, prolonging the recovery time following each effort. Similarly, if the cycle time and percentage of work time within cycle are constant, reductions in force level have the potential to yield reductions in overall EMG activity. Although cycle time was shown to have a minimal effect on overall muscle effort in this study, repetition rate may have important implications related to soft tissue and other anatomical sites leading to cumulative trauma disorders, such as tendinitis and carpal tunnel syndrome. Chatigny and coworkers (1995) reported that even in tasks that were not considered repetitive, the same tendons and joints are exposed to repeated forces from other work tasks. The authors concluded that it is critical to evaluate the physiological effects of the tasks and to identify diversified operations having similar effects on already compromised tissue (Chatigny, Seifert, & Messing, 1995).

In many manufacturing jobs, tasks are externally or machine-paced. In these industrial settings, the standard machine-paced rate is determined by the capabilities of the "average" skilled worker to load, assemble, disassemble, or unload the product (Rodgers, 1987). Unfortunately, the capabilities and characteristics of the average worker may not reflect the diversity of employees in skill and strength. Additionally, the acceptable force level and cycle time, or work-rest ratio, for a given task has not been determined, even for the average worker. It could be argued that the best repetition rate and work-rest ratio is one that the worker self-selects. At a self-selected rate, a worker would be able to use perceived exertion (e.g., discomfort, soreness, pain) as feedback to adjust his or her work-rate. Unfortunately, in many manufacturing jobs, employees are paid on a piece-rate basis that may tend to obscure perceptions of discomfort.

Theoretically, the average force calculated across all force levels and all work-rest cycles in the present study should have been 81 N (the mean of the three hand grip force levels). With an overall average of 50% work within cycle for all trials, the total average force equivalent level, for all trials and all conditions, should have been 40.5 N. However, the average EMG force equivalent values ranged from 67 to 78 N for different cycle times (Figure 2). Several factors may have contributed to the larger than expected values. For instance, other muscle groups not recorded with the EMG may have affected the hand gripping task, such as antagonists and the intrinsic muscles of the hand. For example, the intrinsic hand muscles may have contributed a greater portion of the grip force during the isometric trials than during the repetitive hand gripping trials. This situation would have resulted in calibration curves which somewhat underestimated the EMG-force relationship of the finger flexor musculature. When applied to the repetitive gripping data, the resulting normalized data would have provided the higher than expected muscle efforts found in this study. However, since the same normalization scheme was used for all the data from any individual participant, the relative increase or decrease in overall EMG resulting from manipulation of the three independent variables in this study would be the same, regardless of the exact EMG-force calibration used.

The theoretical average force of 40.5 N assumes a perfect contract-relax sequence. It is not unexpected that muscle contraction time would be longer than gripping time. Muscles do not generate force instantaneously nor do they release their force instantaneously. In a cyclical task, such as the one used in this study, participants must activate the appropriate muscle groups prior to the desired external force delivery and myoelectrical activity decreases in a somewhat exponential manner once the given force level is no longer required. Providing visual feedback of performance, as was done in this study, probably assures these anticipatory and relaxation components of muscle activity. As cycle times become shorter, these anticipatory and relaxation components are likely to take up a progressively greater portion of the available rest time. This effect can be seen in the sample data shown in Figure 1.

Participants in this study may have also overgripped the hand grip device causing the EMG to be elevated. Additionally, in order to simply hold the grip device in the "relax" phase of the work-rest cycle some baseline EMG was required. In an industrial setting, workers in many circumstances are also often required to hold their tools with some amount of baseline muscle activity during the rest phase of the work cycle. In some work settings, mechanical devices are used to decrease the amount of muscle activity during work tasks. The use of a tool balancer, rigid forearm sleeve, and counter balance are examples of mechanical assists to reduce muscle activity and fatigue during repetitive hand gripping tasks.

Although no statistically significant differences were found in mean EMG within work-rest combinations having the same percentage of work time within the cycle and force level, future research comparing longer cycle times and higher force levels may uncover significant differences. The results of this study may have been different if the data had been collected for longer periods of time (e.g., 8 hrs) or from industrial workers who are conditioned for this type of work activity. Additionally, the EMG activity may be affected by the level of underlying muscle fatigue. This would have significant implications for employees working overtime and extended hours.

5. CONCLUSIONS

During a repetitive hand gripping task, differences in mean EMG from the finger flexor musculature resulted from changes primarily in grip force, secondarily in the percentage of work time within the work cycle, and, to a negligible extent, the cycle time or repetition rate of the task As force increased, the level of mean EMG activity increased. As the percentage of work time within the work cycle increased, EMG increased. The results of this study suggest that overall muscle effort, and possibly fatigue, may be reduced during repetitive hand gripping tasks by decreasing the force requirements of the task, by shortening the percentage of work time within the work cycle, and, to a minor extent, by increasing the overall work cycle time. Further studies are needed to determine the effects of such changes in an industrial environment.

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