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It has been recommended that circulatory responses be used as measures of circulatory stress and as a basis of work-rest scheduling. The purpose of this paper is to show how statistical models can be developed and used to describe selected circulatory responses associated with static work elements. Heart rate, mean arterial pressure and cardiac work were modeled as functions of work duration and intensity for four subjects performing sustained static group exertions to exhaustion at 12.5%, 25%, 50% and 75% of maximum strength. Examples and considerations of predicted circulatory responses to static work elements are discussed.

Static work elements and selected circulatory responses

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introduction

Procedures for determining physical work limits and work-rest schedules based on the relationship between circulatory performance and work intensity have been recommended.[1] These procedures are generally accepted by work physiologists and ergonomists for given individuals performing dynamic work.[2,3] However, many industrial jobs involve elements such as standing, sitting, holding, gripping, or hanging on, all of which are static exertions. According to Lind and McNicol[4] and to Burger,[5] circulatory responses are not the same for static and dynamic types of work. Therefore, the use of circulatory performance for the purposes of work-rest scheduling should take into consideration the contributions of static, dynamic, and combined static and dynamic work to the total state of the circulatory system.

The relationship between circulatory performance and work intensity also is of concern because high circulatory loads could have a pathological influence on persons predisposed to circulatory accidents.[5–7] Such persons include those with heart conditions, hypertension, or cerebro-vascular disease. According to the National Center for Health Statistics, the prevalences of known heart conditions in the United States for persons aged 17 to 44 years and for persons aged 45 to 65 years are 24.6 and 37.8 cases per 1000 respectively.[8] While some of the diseased persons are excluded from the work force via natural selection processes, many work in spite of their handicap. In addition, the work force would include those who have circulatory diseases but do not know it. Therefore, the population at risk is probably greater than reported.

The purpose of this work was to show how quantitative models can be developed and used to describe selected circulatory responses during different intensities and durations of static work for male and female workers. It is hoped that this work will lead to future development of models that can be used by ergonomists to estimate the effect of pure static work elements on circulatory performance.

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method

Work duration expressed in seconds and work intensity expressed in percentage of maximum strength were selected as independent variables. Percentage of maximum strength was used so that these results would not be used to predict circulatory stresses associated with given jobs without consideration for the strength capabilities of the working population.

Heart rate, mean arterial pressure, and cardiac work were chosen as dependent variables. All of the circulatory variables were normalized as percentages of the pretest resting values to eliminate resting differences in circulatory variables among subjects.

Heart rate was calculated as the reciprocal of the period between successive QRS complexes of continuous ECG recording. Blood pressure was determined from a recording sphygomomanometer of the nonworking arm; mean arterial pressure was calculated as one-third of the pulse pressure plus the diastolic pressure. Cardiac work was calculated as the product of heart rate and mean arterial pressure.[7]

Two male and two female subjects (22 to 27 years old) all of different strengths, were selected so as not to suppress the intra-sex performance variance. While all of the subjects were considered to be of good health, none of them engaged in competitive athletics. The subjects performed a sustained grip exertion to exhaustion once a day, five days a week, for two to three weeks before testing to familiarize them with the experimental procedures. During this period the subjects were permitted to adjust the grip dynamometer to their preferred power-grip position, which was used during all tests.

The grip dynamometer was constructed from 12.7 mm diameter aluminum lattice rod frame. Strain gauges were attached to a beam that was in turn connected to the handle

TABLE I
Average ± Standard Deviation of Subject Grip Strengths in Kiloponds and Coefficients of Variation in Percentages

Subject	$\bar{X} \pm S$	$(S/\bar{X})$ 100%
Female One	29.5 ± 4.0	13.5%
Female Two	41.5 ± 2.2	5.2%
Male One	57.0 ± 3.2	5.7%
Male Two	79.3 ± 2.1	2.6%

TABLE II
Average ± Standard Deviations of Endurance Times in Seconds at 12.5%, 25%, 50% and 75% of Maximum Strengths

Subjects	Percentage Maximum Strength			
	12.5%	25%	50%	75%
Females	3139 ± 1642	722 ± 47	141 ± 21	39 ± 8
Males	1863 ± 938	419 ± 75	82 ± 23	45 ± 8
Pooled	2501 ± 1317	606 ± 232	112 ± 38	47 ± 15

embraced by the fingers; a second handle anchored to the lattice rod was used to support the palm. Both handles were fitted with a 19 mm outside diameter wooden sleeve.

All subjects were tested once at 12.5% and 50% of maximum strength and twice at 25% and 75% of maximum strength, with all exertions performed to exhaustion. The force of exertion was displayed on a meter in front of the subject. A variable DC offset voltage was used to null the meter at the desired force level. The subjects were required to squeeze the grip dynamometer so as to keep the monitor in the null position.

Each subject's right hand grip strength (also their preferred hand) was determined at the beginning of each test period, then at least thirty minutes were allowed to elapse while the ECG electrodes were connected over the xiphoid process and the manubrium and the sphygmomanometer cuff was placed on the left arm over the brachial artery. The resting heart rate and blood pressure then were recorded. Lastly, the test was performed; circulatory variables were determined as described at 15 to 60 second intervals.

results

The subjects are referred to as Female one (F1), Female two (F2), Male one (M1), and Male two (M2). Descriptive statistics of each subject's strength are given in Table I. The average grip strength ranged from 29.5 to 70.3 kiloponds. The average male, female, and pooled endurance times in seconds at each work intensity are shown in Table II.

The absolute values of the resting heart rate, mean arterial pressure, and cardiac work for each subject are listed in Table III. The remainder of the results are expressed as percentages of the average resting values. The absolute values of the circulatory responses for these subjects can be calculated by multiplying the percentage values by the absolute values of the average resting circulatory variables in Table III. Coefficients of variation ranged from 7% for heart rate and mean arterial pressures to 14% for cardiac work.

The circulatory data for all four subjects during work at 25% and 75% of maximum strength are shown plotted as a function of work duration in Figure 1. The relationship between circulatory performance and static work intensity and duration was modeled via stepwise multiple regression with the following models producing the best fit:

$$HR = 100 + .20\chi w + .0048\chi w^2 - .0000022t^2 + .0000488tw^2 \quad (1)$$

$$MAP = 100 + .93\chi w - .0055\chi w^2 - .0000013t^2 + .0000402tw^2 \quad (2)$$

$$HR \times MAP = 100 + 1.361\chi w - .0000033t^2 + .0000909tw^2 \quad (3)$$

where: HR, MAP, and HR × MAP = heart rate, mean arterial pressure, and cardiac work expressed as percentages of the average resting levels;
t = the work duration expressed in seconds,
χ = 0 when t is less than or equal to 0, (resting before work)
χ = 1 when t is greater than 0, (during work)
w = work intensity expressed as percentage of maximum strength.

A significance level of one percent ($\alpha \leq .01$) was required for inclusion of each term in the models. It was concluded that for these subjects there is a relationship between circulatory performance and the intensity and duration of static work. The values of the circulatory variable predicted during sustained work at 12.5%, 25%, 50% and 75% of maximum strength are shown as a function of work duration in Figure 2.

The coefficient of determination (r^2) between the observed and the predicted values of the circulatory variables was .50 for heart rate, .47 for mean arterial pressure, and .51 for cardiac work. The standard errors of

TABLE III
Average ± Standard Deviations of Pretest-resting Levels of Circulatory Variables

Subject	Mean Arterial Pressure (mm Hg)	Heart Rate (Minutes^{-1})	Cardiac Work (mm Hg/min.)
Female One	85 ± 7	74 ± 7	6220 ± 880
Female Two	76 ± 6	67 ± 5	5300 ± 670
Male One	80 ± 6	68 ± 5	5450 ± 640
Male Two	80 ± 7	76 ± 6	6110 ± 870
Grand Average	81 ± 7	71 ± 8	5760 ± 860

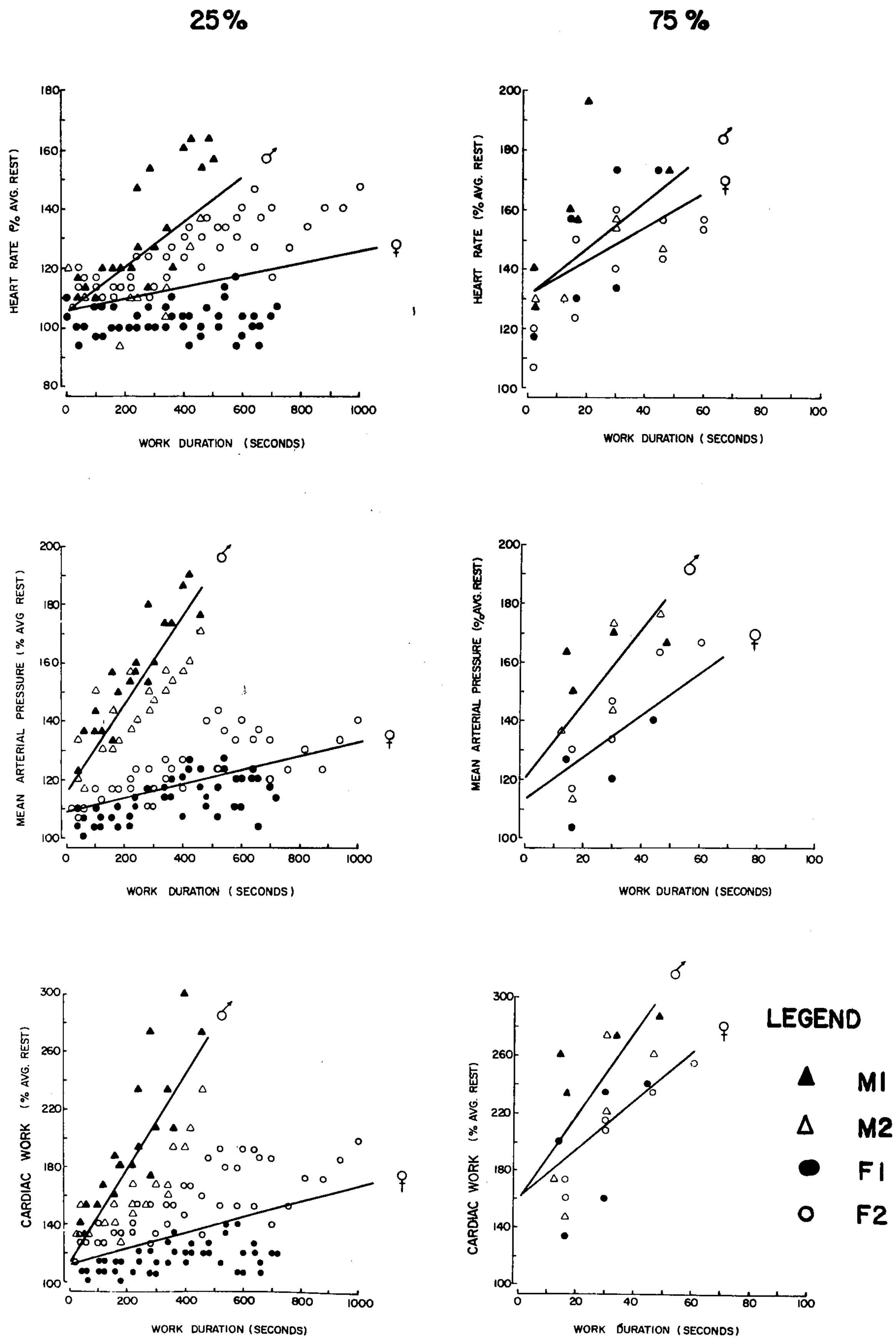

Figure 1 — Observed circulatory responses to sustained static work at 25% and 75% of maximum strength. Regression lines are shown for male and female subjects (Equations 4, 5, and 6).

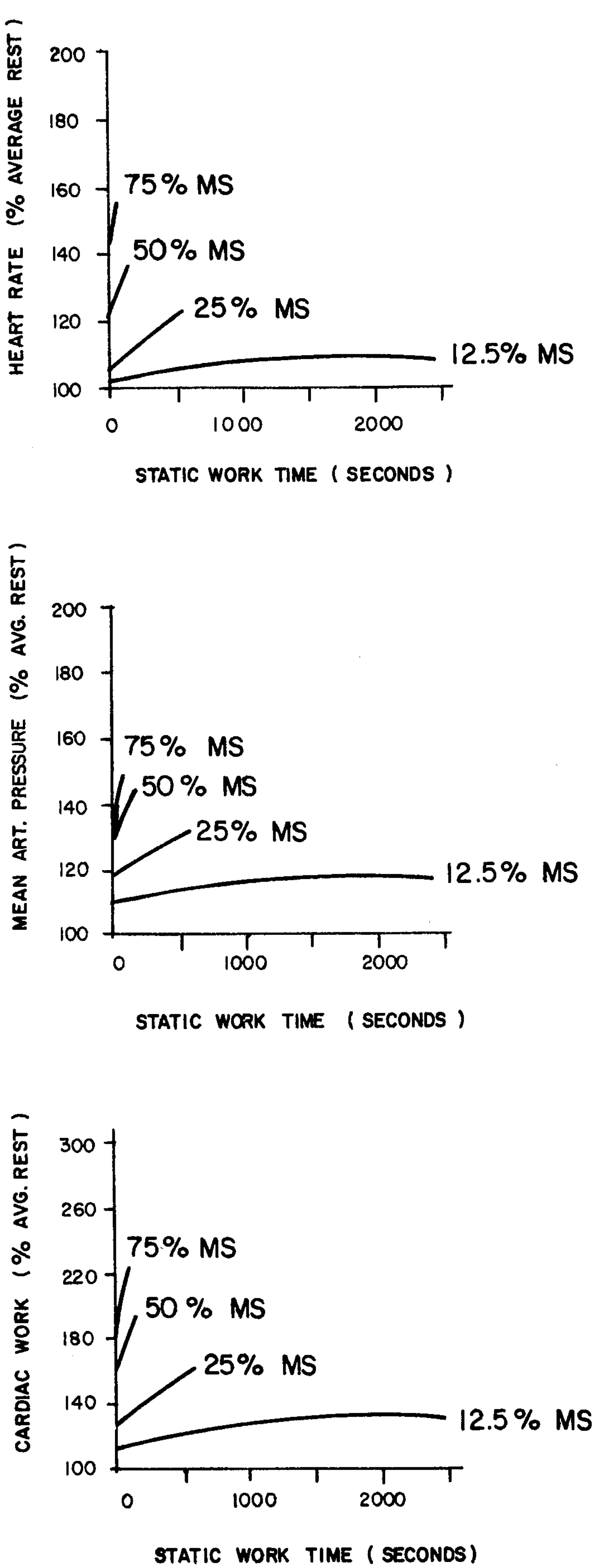

Figure 2 – Predicted average circulatory responses are shown for all four subjects working at 12.5%, 25%, 50%, and 75% of maximum strength (Equations 1, 2, and 3).

regression expressed as percentages of the average resting values were 12.8% for heart rate, 14.3% for mean arterial pressure, and 29.4% for cardiac work.

Since the circulatory variables are expressed as percentages of their average resting values, they must be equal to 100% of their average resting values when the work duration is less than or equal to zero. For this reason, work intensity is included in the circulatory models as an interaction of the variable χ, where variable χ is defined as zero for work durations less than or equal to zero, and as one for durations greater than zero. The significance of the interactions between work intensity and the variable χ indicates that the values of the circulatory variables change abruptly within the first few seconds after the onset of work. At the onset of work (between 12.5% to 75% of maximum strength) the average heart rate increased to values of 103% to 142%; the average mean arterial pressure increased to values of 111% to 138%; the average cardiac work rate increased to values of 117% to 202%. (See equations 1, 2, 3, and Figure 2.)

The circulatory models (Equations 1, 2 and 3) also contain negative quadratic effects of work duration and positive interactions of work duration and intensity. The interactions indicate that the values of the circulatory variables increase as functions of work duration, and that the rate at which the circulatory variables increase increases as a quadratic function of work intensity. Thus, not only are the initial values of the circulatory variables greater at high work intensities than at low intensities, the values also increase more rapidly at high work intensities than at low intensities. The negative quadratic effect of work intensity indicates that the values of the circulatory variables level off during prolonged exertions, longer than 1500 seconds. During exhaustive static work between 12.5% and 75% of maximum strength, it is predicted that the average heart rate reaches values of 116% to 154%, the average mean arterial pressure reaches values of 118% to 149%, and the average cardiac work reaches values of 132% to 226%.

To evaluate the effect of gender on the relationship between static work intensity and duration and circulatory performance, a forward stepwise regression procedure was used to fit the following models to the data:

$$HR = 100 - 6.5\chi + .51\chi w + .0278t - .00411tw + .0001513tw^2 - .0219tg + .00308twg \quad (4)$$

$$MAP = 100 - 10.4\chi + 1\chi w - .0092\chi w^2 + .0449t - .00574tw + .0001956tw^2 + 6.8\chi g - .0994tg + .00902twg \quad (5)$$

$$HR \times MAP = 100 - 8.5\chi + .89\chi w + .0933t - .0127tw + .000447tw^2 - .1889tg + .0182twg \quad (6)$$

where: HR, MAP and HR × MAP = heart rate, mean arterial pressure, and cardiac work expressed as percentages of the average resting levels;
- t = the work duration expressed in seconds,
- χ = 0 when t is less than or equal to 0, (resting before work)
- χ = 1 when t is greater than 0, (during work)
- w = work intensity expressed as percent of maximum strength.
- g = 0 for female, 1 for male

Requiring a significance level of $\alpha \leqslant .01$, it was concluded for these subjects that the relationship between intensity and duration of static work and circulatory performance is affected by gender. The predicted circulatory responses during sustained work at 25% and 75% of maximum strength are shown plotted as a function of duration in Figure 1.

The coefficients of determination (r^2) between the observed and the predicted values of the circulatory variables are .68 for heart rate, .86 for mean arterial pressure, and .80 for the cardiac work. The standard errors of regression expressed as percentages of the average resting values are 10.3% for the heart rate, 7.5% for mean arterial pressure, and 19.7% for cardiac work.

The pressure model (Equation 5) contains a significant interaction between the χ and the gender variables. This interaction indicates that at the onset of static work, the mean arterial pressure increases more for the male subjects than for the females; the difference between males and females is equal to 6.8% of the average resting pressure (see Figure 1).

All of the circulatory models include significant interactions between work duration and gender and among work duration, work intensity and gender. These interactions indicate that during sustained static work at a given percentage of maximum strength the values of the circulatory variables increase more rapidly for the male subjects than for the females; however, the difference between the sexes decreases with increasing relative work intensity (see Figure 1).

The addition of these gender parameters to the circulatory models increases the explained variances and decreases the residual errors considerably. The correlation coefficient (r^2) is increased from .50 in Equation 1 to .68 in Equation 4, from .47 in Equation 3 to .86 in Equation 5, and from .51 in Equation 3 to .80 in Equation 6.

Heart rate, mean arterial pressure, and cardiac work rapidly returned to the pretest resting average. A least squared error regression procedure was used to fit polynomial, reciprocal and logarithmic models to this data. However, none of these models accounted for more than a very small portion of the observed variance. These results indicate that in most cases the circulatory variables are nearly equal to the pretest resting average within one minute.

discussion

These circulatory responses can only be compared with the results of other investigations in a qualitative manner. Circulatory responses are related to work duration and relative intensity, therefore, it is not possible to rigorously compare responses among individuals or populations without fitting some kind of statistical model to the data from the individuals or populations being compared. A review of the available literature did not reveal that previous investigators had fitted such models to their data.

The grip dynamometer used in this study was custom built to have minimal compliance. It would not be proper to directly compare the grip strength measurements made with this device in Table I with measurements made on other devices. Work by other investigators shows that isometric grip strengths measured with a low compliance device averaged 20% greater than corresponding measurements with a commercially available device with greater compliance.[10]

Since the point of exhaustion was chosen arbitrarily, there is no reason to expect the endurances shown in Table II to be the same as those reported by other investigators. It suffices to say that both the averages and standard deviations decrease with increasing work intensity. These data are shown only to indicate the range of work durations in which circulatory responses were recorded.

Humphreys and Lind[9] reported that systolic and diastolic blood pressure increases with work duration and relative intensity for persons performing static grip exertions between 30% and 70% of maximum strength; this finding is in agreement with predictions based on Equations 2 and 5 and shown in Figures 1 and 2. It can be seen from these figures that at 12.5% of maximum strength, the values of the circulatory variables seem to reach a steady state, while at high work intensities the values increase continuously throughout the duration of the exertion. These predictions are in agreement with the findings of Lind, *et al.*[11]

It is noteworthy that there are significant inter-subject variances; a large part of these variances are attributable to gender differences (see Equations 4, 5, and 6). These variances could be due to strength difference between the sexes. Quigley has shown a positive relationship between mean arterial pressure and muscle strength for subjects performing static elbow flexion.[12] Quigley interpreted this finding as an adaptation of the circulatory system of strong people to a large muscle mass. Such an interpretation also could account for the observed difference in circulatory performance between male and female subjects (Figure 1). Whatever is the case, the difference between the variance explained by models 1, 2, 3 and 4, 5, 6 illustrate the need to consider subject attributes in addition to relative work intensity.

Although only grip exertions were considered in this study, equivalent responses would be expected for other muscle groups of a given subject. Lind and McNicol[4] reported that at a given relative static work intensity, the same circulatory or blood pressure rise was obtained during a grip exertion that was obtained during planter flexion of the foot. These investigators concluded that when a person performs static work, the circulatory response is related to the relative work intensity of the muscle that is contracting at the highest proportion of its strength and that the response is not affected by the size of the muscle.

Only pure static work was considered in the present study; however, the work of other investigators indicates that models based on pure static work should be valid for tasks that simultaneously involve static exertions of one muscle group and dynamic exertions of other muscle groups. Lind and McNicol[4] reported that the circulatory response of persons performing static grip exertions up to 50% of

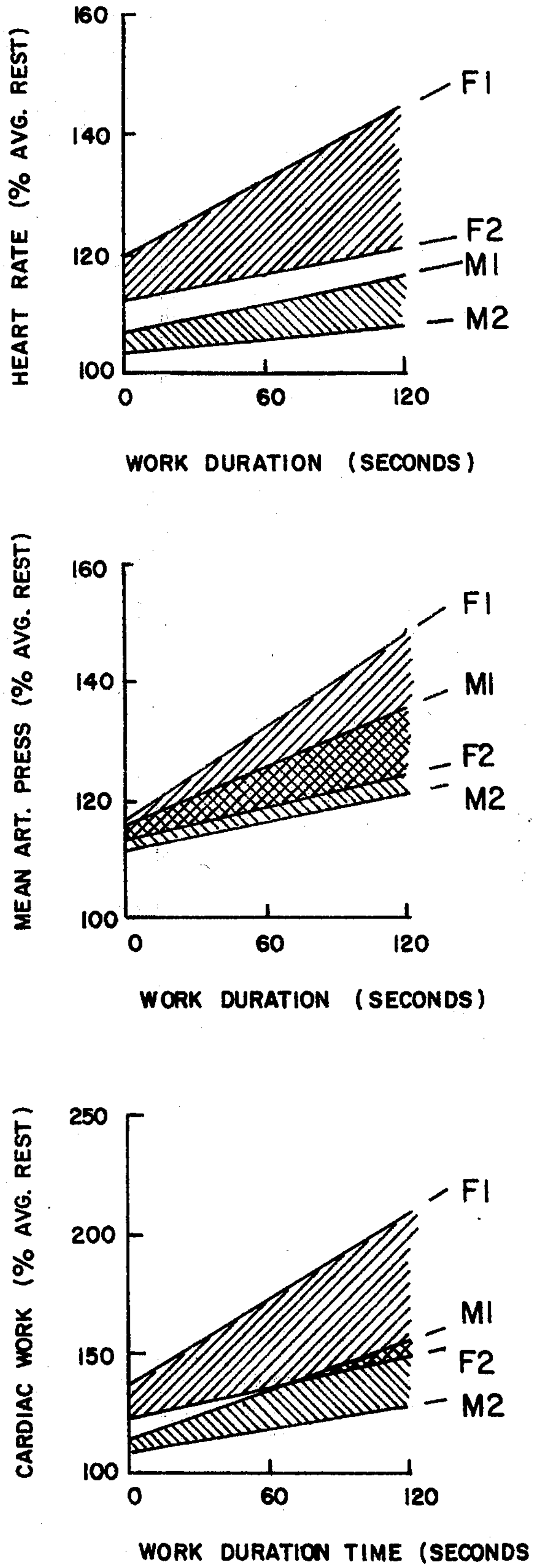

Figure 3 — Predicted circulatory responses that would be obtained for all four subjects holding a 15 Kp load are shown above (Equations 4, 5, and 6).

maximum strength was not affected by walking at rates as high as 1.7 L O_2/min: the circulatory response was diminished at higher work intensities. Jackson, *et al.*,[13] also reported a positive relationship between relative static work intensity, heart rate, and mean arterial pressure for persons carrying weights and walking on a treadmill. Additional research is required to determine the relationship between circulatory responses and alternating static and dynamic exertions of the same muscle group.

Circulatory responses associated with static work are more stressful than those encountered in dynamic work where cardiac pumping is assisted by the rhythmically contracting muscles that return blood to the heart and decrease the total peripheral resistance during dynamic work. During static work the heart must do all of the pumping against an unaltered total peripheral resistance.[4] Hence, the mechanical efficiency of the heart is less and the mechanical work load is greater in static work than in dynamic work.[14,15] Based upon findings reported by previous investigators,[16,17] Jackson, *et al.*,[13] concluded that angina pectoris would occur at lower work intensities for combined dynamic and static work than those for pure dynamic work; these investigators suggested that the static work associated with carrying a suitcase is a major factor in so-called "airport angina".

As was pointed out in the Introduction, high circulatory loads associated with static work could have a pathological influence on the health of persons predisposed to circulatory disease. The National Heart and Lung Institute estimates that high blood pressure is a factor in 68% of all first heart attacks and in 75% of all first strokes.[18] Models of the type developed, could be used to estimate circulatory stresses of certain work elements. This information could be used by medical personnel for placement of persons with circulatory handicaps. This information could be used by engineers to design jobs with minimal circulatory stresses.

So far, circulatory responses among different subjects have been compared for given levels of relative work intensity; since men and women frequently perform the same job, it is necessary to compare their responses for a given level of absolute work intensity. Responses to a given level of absolute force can be estimated from Equations 4, 5, and 6 for the subjects considered in this study. For this comparison a load, such as a suitcase, that is held in the hand at the side, is considered. It is assumed that for this posture the hand is the strength limiting joint. For the female subjects in this study, a 15 kg load would constitute relative work intensities of 50%, and 36% of maximum strength; for the male subjects, this load would constitute work intensities of 26%, and 19% of maximum strength (see Table I). The predicted (Equations 4, 5, and 6) circulatory responses during two minutes of this work are shown plotted as functions of work duration in Figure 3. After one minute of this work predicted heart rate ranges from 105% of the average resting level to 128%; mean arterial pressure ranges from 117% of the average resting level to 131%; and cardiac work ranges from 119% of the average resting level to 170%. The circulatory responses are greatest for the Female One and least for the Male Two because the female is working at a much greater relative work intensity than is the strong male. The circulatory responses for the strongest female (F2) and weakest male (M1) tend to overlap because there only a small difference in relative work intensities between the strong female and weak male, and because for a given level of relative work, the male subjects have greater circulatory responses than do the female (see Figure 1).

summary

Selected circulatory responses to single sustained exertions were modeled for four young healthy subjects under laboratory conditions. This work is intended to illustrate how such models can be developed and used to predict circulatory responses for static work elements. Additional research is required to estimate model parameters for the work force. Such work should include validation studies under actual work conditions as well as in such diverse populations as the elderly and hypertensive.

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