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Muscular fatigue and maximum endurance time assessment for male and female industrial workers

Zhanwu Zhang [a], Kai Way Li [b,*], Wei Zhang [a], Liang Ma [a], Zhenguo Chen [a]

[a] Department of Industrial Engineering, Tsinghua University, Beijing 100084, China
[b] Department of Industrial Management, Chung Hua University, 707 Sec 2 WuFu Road, Hsin-Chu 300, Taiwan

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ABSTRACT

A single arm pushing experiment was conducted in an electronic factory in Yantai, China to assess muscular fatigue using the theoretical models of muscular strength and maximum endurance time (MET) developed by Ma et al. (2009). Seventy seven workers, including 38 males and 39 females, participated in the study. The muscular strength of pushing was measured after the subject pushed a stick, with a force of 2.5 kgf, for 0.5, 1.0, 1.5, 2.0, 2.5, and 3.0 min. Fatigue rate was determined based on a regression approach. In addition to the theoretical model, the MET for such a pushing task was also determined using four empirical models in the literature. The results indicated that females were more resistant to muscular fatigue than males in the pushing task. The results of the muscular strength prediction show that the predictability of the muscular strength model is acceptable. The prediction errors for muscular strength for female subjects were significantly lower than those of the male subjects. The predicted MET using the theoretical model, with a group constant k, was highly correlated with those using the empirical models compared in the current study.

Relevance to industry: Muscular fatigue is common on workplace. Assessment of muscular fatigue is helpful not only in providing reasonable work-rest design but also in reducing musculoskeletal injures for workers performing physical works.

1. Introduction

Muscular fatigue is common for people performing physical works. It is defined as “any exercise-induced reduction in the capacity to generate force or power output” (Vøllestad, 1997) or alternatively the “reduction in the ability to exert force in response to voluntary effort” (Chaffin et al., 1999). It is the physiological phenomenon that “describe the gradual decrease in the force capacity of muscle or the endpoint of a sustained activity and can be measured as a reduction in muscle force, a change in electromyographic (EMG) activity or an exhaustion of contractile function” (Enoka and Duchateau, 2008). Assessment of muscular fatigue is one of the fundamental issues in quantifying workload and work/rest arrangement so as to provide basis for job design/redesign.

Muscular fatigue may be assessed directly or indirectly. Measurements of the reduction of maximum voluntary contraction (MVC) or force output after performing a forceful exertion for a period of time are direct measurements. Testing the EMG, endurance time, or muscle fiber twitch interpolation, on the other hand, provide indirect measure of muscular fatigue (Vøllestad, 1997). When measuring the reduction of the MVC, the subject was normally requested to apply a force against an external load. The reduction of the MVC may, then, be fitted using a certain function. The exponential function has commonly been adopted for this purpose (Wood et al., 1997; Roman-Liu et al., 2004, 2005; Iridiastadi and Nussbaum, 2006). Models of muscle fatigue have been established based on fitted functions using muscular strength data under different task conditions. Although different prediction models have been established, most models were derived using data from a relatively small sample. Individual characteristics which could result in variations of muscular fatigue have been neglected.

Ma et al. (2009) developed a muscle fatigue model based on the same concept that muscular strength decrease when exerting against an external load for a period of time due to fatigue. The following equation was proposed to describe such a decrease:

$$F(t) = \mathrm{MVC}e^{-k\frac{F_{\mathrm{load}}}{\mathrm{MVC}}t} \quad (1)$$

where $F(t)$ is the muscular strength at time t, MVC is the maximum voluntary contraction of the muscle, F_{load} is the muscle force

* Corresponding author. Tel.: +886 3 5186583; fax: +886 3 5186575.
E-mail addresses: kaiway.li@gmail.com, kai@chu.edu.tw (K.W. Li).

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required to balance the external load, and k is the fatigue rate, or fatigability, for the muscle group and is a constant. $F(t)$ is equivalent to MVC when t is equal to zero. Taking natural logarithm on both side of Eq. (1), we have:

$$\ln\left(\frac{F(t)}{\text{MVC}}\right) = -k\frac{F_{\text{load}}}{\text{MVC}}t \tag{2}$$

Regression equation without intercept may be established using the left-hand-side of Eq. (2) as the dependent variable and t as the independent variable if $F(t)$ and MVC are known. In other words, Eq. (2) may be represented as Eq. (3):

$$y = b \times t \tag{3}$$

where y is equal to $\ln\left(\frac{F(t)}{\text{MVC}}\right)$ and b is the regression coefficient.

The fatigue rate may be determined using the following equation when b is known:

$$k = -b\frac{\text{MVC}}{F_{\text{load}}} \tag{4}$$

The fatigue rate is the parameter describing the susceptibility to fatigue or the tendency to get tired or lose strength. It is determined by factors such as muscle group, muscle fiber composition, age, gender, and so on (Ma et al., 2011). It may be used to indicate the characteristics of either an individual or a sample population. The reciprocal of fatigue rate may be defined as fatigue resistance (or m) to describe the capability of muscle to resist the developing of fatigue. Ma et al. (2011) suggested that determination of either fatigue rate, or alternatively fatigue resistance, is beneficial to work-rest design for industries.

The maximum endurance time (MET) has also been adopted to assess fatigue indirectly so as to schedule work-rest allowance for workers. Determining the MET requires a subject to apply a force at a certain level and to measure the maximal duration for such a force exertion. MET models for different muscle groups under different working conditions have been established (Rohmert, 1960, 1973; Sato et al., 1984; Rohmert et al., 1986; Bishu et al., 1995; Kanemura et al., 1999; Mathiassen and Ahsberg, 1999; Garg et al., 2002; Law and Avin, 2010). Most of the MET models in the literature adopted the negative exponential functions with two asymptotic tendencies. The MET models reported in the literature may be used to determine work-rest allowance. However, the results based on those models could be quite different (El ahrache et al., 2006).

Ma et al. (2009, 2011) proposed a natural logarithm model to determine the MET for a specific task using Eq. (5).

$$\text{MET} = \frac{\ln\left(\frac{\text{F}_{\text{load}}(t)}{\text{MVC}}\right)}{k\frac{\text{F}_{\text{load}}(t)}{\text{MVC}}} = -\frac{\ln(f_{\text{MVC}})}{k(f_{\text{MVC}})} \tag{5}$$

The MET in this equation is the maximum time that muscular strength decreases from MVC to the external force exertion level. The f_{MVC} is the ratio of the external load to the MVC when the external load is a constant. The fatigue rate, or k, may be assigned 1 in general conditions or a certain constant to indicate the individual attribute of the subject.

The objectives of this study were to assess the muscle fatigue in single-arm pushing for male and female industrial workers using the muscular fatigue model from Ma et al. (2009, 2011) and to compare the MET between male and female subjects using the MET models by Ma et al. (2009, 2011) and four shoulder models in the literature. In addition, the effects of body mass index (BMI) on the fatigability of the pushing task were also examined.

2. Methods

2.1. Subjects

Seventy seven workers, including 38 males and 39 females, in an electronic factory in Yantai, China participated in the study as human subjects. All the participants had been working in their current positions for one year or longer. All of them did not have history of musculoskeletal injury. The subjects were compensated for their participation in the study and had signed informed consent before the experiment. Their age, body weight, stature, and BMI are shown in Table 1.

2.2. Apparatus

An arm test system was installed. In this system, a stick with an extra weight hanging in the middle was suspended using wires in front of an electronic scale (Shanghai Yousheng® Weighing Apparatus, BS-30KA) which was mounted on the wall. The gravity of the stick and the weight was 10 kgf. The stick was tilted at an angle of 14.5° to the horizon. The height of the stick was approximately the shoulder height of the subject when she/he was sitting upright. The wires were adjusted so that the distal end of the stick just touched the scale when the subject was pushing with fully extended elbow posture. The pushing force on the stick along the stick direction was, therefore, 2.5 kgf (10 kgf $\times$ sin14.5°) (see Fig. 1).

2.3. Push test

While sitting, the subject was required to push the stick, using his/her right arm, to touch the scale and to maintain the posture for a certain period of time. This task was designed to simulate an operation to drive a screw in the front. The operator needs to push when performing such a task using a powered screwdriver. The pushing force (F_{load}), as explained in Section 2.2, was 2.5 kgf. There were seven time periods (t): 0, 0.5, 1, 1.5, 2, 2.5, and 3 min. The pushing strength of the subject after pushing for a period of time, or $F(t)$, was measured by asking the subject to push the stick as hard as he/she could for five seconds. This measurement was conducted immediately after each push task was completed. The peak of the readings on the scale was recorded as $F(t)$. The pushing strength reading for $t = 0$, or $F(0)$, was recorded as the MVC of subject. After each measurement, the subject took a break for three minutes or longer until next test (El ahrache and Imbeau, 2009).

2.4. Data analysis

All the subjects are workers in the factory. They work in different work shifts. The subjects participated in the experiment based on their availability. The experiment was performed using a randomized completely block design. Each subject was treated as a block. The trials were randomized within each block. A total of 539 (77 subjects $\times$ 7 sessions) trials were performed. Regression analyses were performed for the data for each subject using Eq. (3). The fatigue rate, or k, was calculated using Eq. (4) and the fatigue resistance was the reciprocal of k. Predicted muscular strength after applying F_{load} for a time period t may, then, be calculated using Eq.

Table 1
Age, body weight, stature, and BMI of the subjects.

	Age (yrs)	Stature (cm)	Body weight (kg)	BMI (kg/m^2)
Male ($n = 38$)	21.8 (±2.1)	169.8 (±6.7)	61.6 (±10.4)	21.3 (±3.0)
Female ($n = 39$)	21.9 (±2.1)	160.5 (±5.2)	54.9 (±10.8)	21.3 (±4.3)

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Fig. 1. Apparatus & experimental setup.

(1). A two way (gender × BMI) analysis of variance (ANOVA) was performed to test the effects of gender and the BMI on fatigue rate. For this analysis, the subjects were divided evenly into two groups according to their BMI values. The subjects with BMI values over the medium were pooled in one group. The rest of the subjects were pooled in the second group. Pearson's correlation coefficients between measured and predicted pushing force were calculated. Statistical analyses were performed using the SPSS® 19.0.

3. Results

Fig. 2 shows the pushing strength after pushing the stick for a time period t for male (A) and female (B) subjects, respectively. The measured strengths for each subject were marked using the symbol "×". The dark squares on the two figures mark the mean strengths for all subjects. The dotted lines above and below the solid line indicate the ranges within one standard deviation. The pushing strength at time 0 (or MVC) for male and female subjects were 12.43 (±2.97) and 7.38 (±1.54) kgf, respectively. The difference was significant at $p < 0.0001$. In addition to MVC, males had significantly ($p < 0.0001$) higher pushing strength at all the tested time periods than female subjects. Fig. 2 shows decrease of pushing strength during the test period. For male subjects (See Fig. 2(A)), the mean pushing strength at time 0.5, 1, 1.5, 2, 2.5, and 3 min were 91.1%, 83.1%, 75.9%, 69.4%, 63.6%, and 58.2% of the MVC, respectively. For females (see Fig. 2(B)), the mean pushing strength became 89.4%, 80.1%, 71.8%, 64.4%, 57.8%, and 51.9% of the MVC accordingly. The drop of pushing strength for females was slightly higher than those of the males.

One regression equation was obtained for each subject using Eq. (3). The coefficient of determination (Neter et al., 1989), or R^2, ranged from 0.80 to 0.99 for males and from 0.89 to 0.99 for females, respectively. Both the fatigue rates and fatigue resistances were calculated. The ANOVA results showed that gender was a significant ($p < 0.001$) factor affecting the fatigue rate. Male subjects were found to have significantly higher fatigue rate (0.93 ± 0.38 min^{-1}) than their female (0.66 ± 0.22 min^{-1}) counterpart. Alternatively, the female subjects had significantly ($p < 0.05$) higher fatigue resistance (1.35 ± 0.38) than those of males (1.72 ± 0.66). The effects of the BMI on fatigue rate were not statistically significant.

Predicted pushing strength was determined using Eq. (1) after k was calculated based on the regression results. Fig. 3 shows the predicted and measured normalized pushing strength for one male

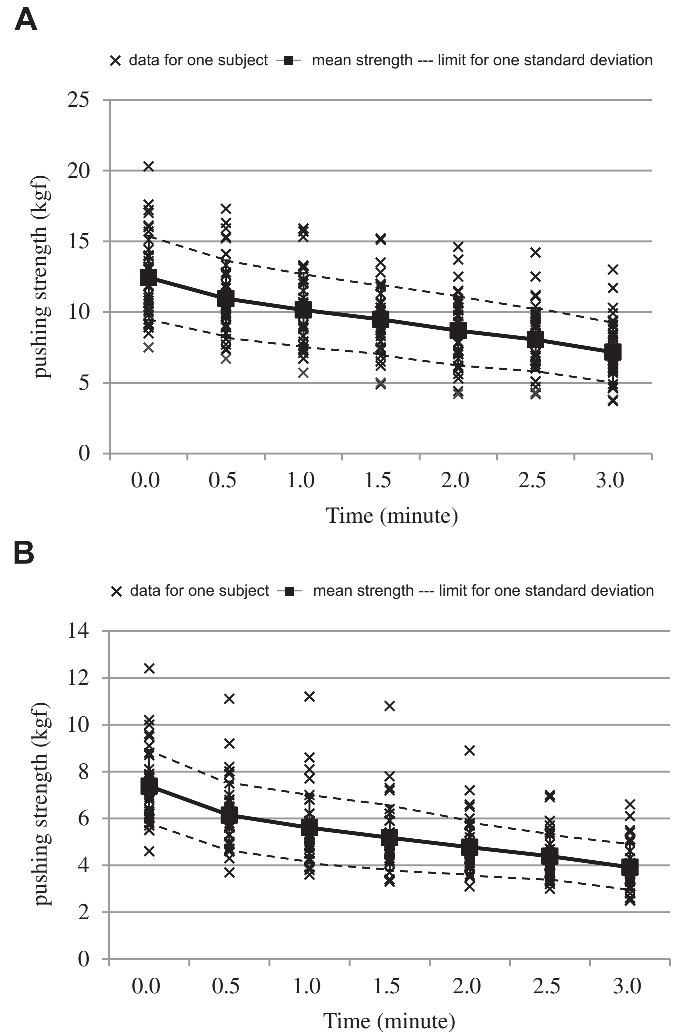

Fig. 2. Pushing strength for male (A) and female (B) subjects.

subject with k equals to 0.95. The regression equation is $y = e^{-0.22t}$ with an R^2 of 0.98. Predictive equations for normalized pushing strength for males and females may be derived using the averaged pushing strength data from the two groups using Eq. (1):

$$\begin{aligned} y &= e^{-k(F_{load}/MVC)t} \\ &= e^{-0.93(2.5/12.43)t} \quad \text{for males} \end{aligned} \tag{6}$$

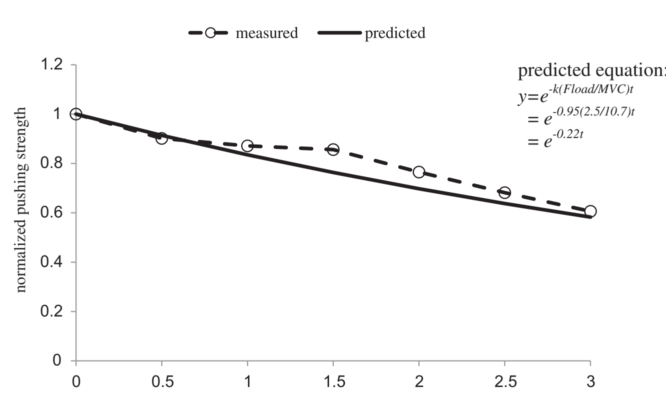

Fig. 3. Normalized pushing strength for one male subject.

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$$y = e^{-k(F_{load}/MVC)t} = e^{-0.66(2.5/7.38)t} \quad \text{for females} \tag{7}$$

where y is the normalized pushing strength and t is the time period.

Pearson's correlation coefficients between the measured and predicted pushing force were calculated using Eqs. (6) and (7). For female subjects, the Pearson's correlation coefficients ranged from 0.95 to 0.98. For males, the Pearson's correlation coefficients ranged from 0.94 to 0.98. A mean absolute deviation (MAD) was defined to compare the difference between the actual and predicted pushing strength after pushing the stick for a time period t using the following equation:

$$\text{MAD} = \frac{1}{n}\sum_{i=1}^{n}|\text{actual value} - \text{predicted value}|$$

The MADs for the time period t were shown in Table 2. The MAD for all the time periods except 0.5 min for females were significantly ($p < 0.05$ or lower) lower than those of males.

As shoulder flexion was involved primarily in the pushing task, four shoulder models in the literature (Sato et al., 1984; Rohmert et al., 1986; Mathiassen and Ahsberg, 1999; Garg et al., 2002), in addition to the model of Ma et al. (2009, 2011), were used to determine the MET for comparison purposes. The MET for both male and female subjects conducted the pushing task in the current study were calculated using the five MET models in the literature and the results are shown in Table 3.

The correlations of the MET values between the model of Ma et al. (2009) and the other four models for male and female subjects are shown in Fig. 4, respectively. In this figure, k was assigned 1 in determining the MET using Eq. (5) for all subjects to remove individual effects so as to make group comparisons with those of the four other models. Fig. 4 shows strong correlation between the models of Ma et al. (2009) and the other four for both male (A) and female (B) subjects. The Pearson's correlation coefficients of the MET from Ma et al. (2009) and from the other four were all above 0.99 for both male and female subjects' data. However, the data in Fig. 4 show that the MET calculated using Eq. (5) are, in general, lower than those using the model of Garg et al. (2002) but are higher than those using the models from Rohmert et al. (1986), Mathiassen and Ahsberg (1999), and Sato et al. (1984). The deviations of the MET values of Rohmert et al. (1986), Mathiassen and Ahsberg (1999), and Sato et al. (1984) from those of Ma et al. (2009) were becoming larger with increasing time period.

4. Discussion

A simple pushing task was carried out by each subject in this study. This pushing task, simulating a screw-driving operation, represents only a small part of industrial tasks and may not be a typical task that the workers perform during their daily duties. There was no postural change during the test. The pushing involved shoulder flexion, elbow extension, and wrist extension of the arm.

Table 2
Mean absolute deviation of the predicted strength (kgf).

Time (min)	Male	Female
0.5	0.71	0.51
1.0*	0.65	0.43
1.5*	0.50	0.32
2.0***	0.43	0.18
2.5*	0.38	0.26
3.0**	0.46	0.29

*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

While pushing, the subject had to exert forces against external loads both in the stick direction and in vertical (gravity). As a result, the strength measurements in the pushing direction might be lower than those in a pure pushing task. The pushing force was monitored using an electronic scale. This scale reports peak force only. The possible effects of acceleration on the pushing force were neglected. This could be one of the limitations of the study.

There are additional limitations of the study such as the external force to maintain the pushing was not adjusted to a ratio of the MVC but was controlled at 2.5 kgf. The consideration for such an arrangement was that for most industrial jobs, the force requirements are not adjustable to each individual but are controlled at a certain level. The %MVC of the pushing force was, therefore, somewhat different for each subject. The force required to maintain the pushing during the trial (2.5 kgf) was 12%–33%, or 21% on average, of the MVC for the male subjects. But this force was 20%–54%, or 35% on average, of the MVC for the females. The female subjects were applying a relatively higher force than the males during the trial. The interpretation and implication of our data, therefore, are only valid within those %MVC ranges.

The BMI is commonly used to indicate thinness, or alternatively fatness, of a person. High BMI implies high percentage of body fat and/or muscle mass. Highly muscular people, such as bodybuilders, may have high BMI values as compared to others with the same height. Over 62% (48/77) of our subjects were within the normal BMI range (18.5–24.99 kg/m^2) suggested by the World Health Organization (WHO, 2000). This percentage is slightly higher than the national percentage (58.9%) of the Chinese population (BMI database, WHO). It was hypothesized that the BMI could be a significant factor affecting the fatigue rate as it is one of the commonly used indicators to represent individual characteristics of the body. This hypothesis was, however, not supported by our results. The insignificance of BMI on the fatigue rate may be attributed to the fact that the pushing task in the current study involved mainly shoulder flexion and elbow and wrist extension of right arm while the BMI is an index for the whole body. The BMI may be affected by the percentage of body fat and lean muscle mass in all body segments. It may simply not be a sensitive indicator to the fatigability of the muscle groups involved in our pushing task.

The results of both the fatigue rate and fatigue resistance indicated that females were more resistant to muscular fatigue than males in the pushing task. This was consistent with those in the literature (Hicks et al., 2001; Hunter et al., 2006; Avin et al., 2010). The causes of gender difference in muscular fatigue have been grouped in four aspects in the literature i) muscle mass, ii) muscle composition, iii) neuromuscular activation, and iv) glycolytic pathway utilization (Clark et al., 2005; Larivière et al., 2006; Enoka and Duchateau, 2008; Hunter, 2009; Avin et al., 2010). It is believed that these causes contributed to the fatigue rate outcomes of the pushing task in the current study.

The results of the muscular strength prediction showed that the predictability of Eq. (1) is acceptable. The MAD results in Table 3 indicated that the prediction errors for female subjects were significantly lower than those of the male subjects in five out of six testing periods. The prediction errors for male subjects showed a trend of monotonic decrease as the testing period increase. This trend was, however, not observed for female subjects. The discrepancy between the two genders might be attributed to the relative force exertion difference between male and female subjects. The force exertion (%MVC) for female subjects was, on average, 14% higher than that of their male counterpart. This implies a relatively low prediction error may be anticipated at a high force exertion level when using the strength prediction equation from Ma et al. (2009). In addition to the gender difference, the MAD results in Table 3 showed that errors in predicting the

Table 3
MET (mean ± std) calculated using different models (unit:minute).

	Equation	Male subjects	Female subjects
Ma et al.	$\mathrm{MET} = -\frac{\ln(f_{\mathrm{MVC}})}{k f_{\mathrm{MVC}}}$ $k = k_i$ for subject i	9.82 (±4.59)	5.11 (±1.80)
	$\mathrm{MET} = -\frac{\ln(f_{\mathrm{MVC}})}{k f_{\mathrm{MVC}}}$ $k = 0.93$ for males	8.87 (±3.38)	–
	$\mathrm{MET} = -\frac{\ln(f_{\mathrm{MVC}})}{k f_{\mathrm{MVC}}}$ $k = 0.66$ for females	–	4.93 (±2.03)
	$\mathrm{MET} = -\frac{\ln(f_{\mathrm{MVC}})}{k f_{\mathrm{MVC}}}$ $k = 1$ for all subjects	8.11 (±4.59)	3.26 (±1.34)
Rohmert et al.	$\mathrm{MET} = 0.2955\, f_{\mathrm{MVC}}^{-1.658}$	4.34 (±1.74)	1.82 (±0.66)
Mathiassen & Ahsberg	$\mathrm{MET} = 40.609\exp(-9.7\, f_{\mathrm{MVC}})$	5.76 (±2.58)	1.64 (±1.11)
Garg et al.	$\mathrm{MET} = 0.5618\, f_{\mathrm{MVC}}^{-1.7551}$	9.72 (±4.13)	3.86 (±1.49)
Sato et al.	$\mathrm{MET} = 0.398\, f_{\mathrm{MVC}}^{-1.29}$	3.18 (±0.98)	1.62 (±0.44)

pushing strength became large when the testing period was at 3 min. The implication was that the prediction error could become large when the fatigue was above a certain level or the testing period was approaching the MET.

In ergonomics, identifying individual factor affecting dependent variables is helpful to understand the phenomenon studied. When targeting job design issues in industry, however, group behaviors

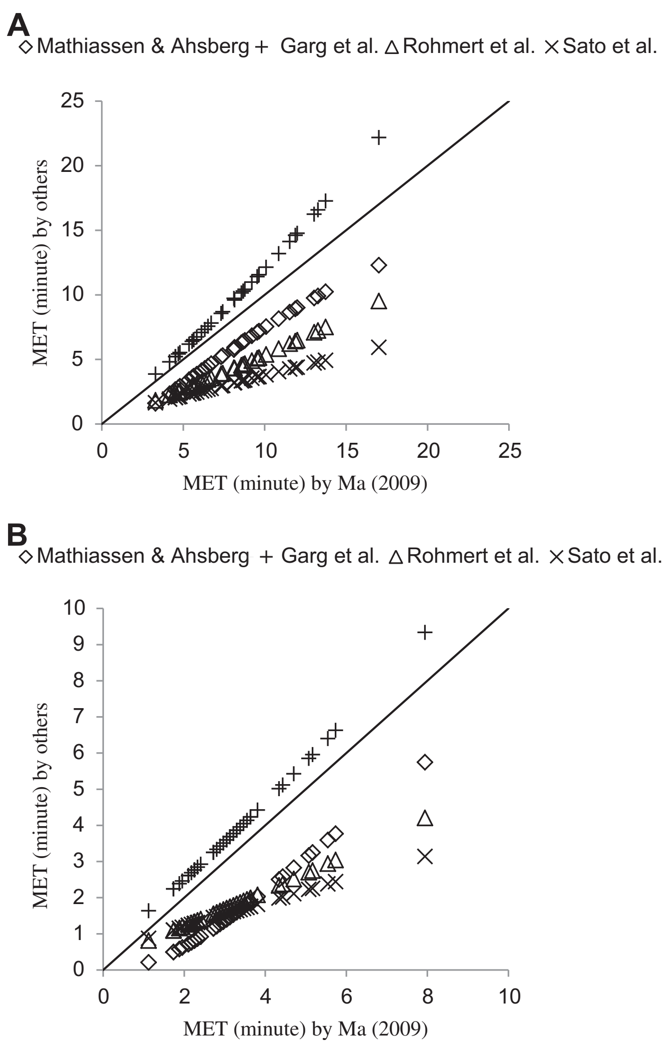

Fig. 4. Correlation of the predicted MET between Ma et al. (2009) and others for male (A) and female (B) subjects.

are more commonly considered than individual characteristics. A unique part of both the force capability equation (Eq. (2)) and the MET model (Eq. (5)) of Ma et al. (2009, 2011), as compared to other models in the literature, is that the models adopt k, or the fatigability, to predict muscular fatigue. A specific k as determined from a regression analysis may be used to represent individual characteristics. The k may be assigned 1 for general population. In addition, it may also be assigned a certain constant to represent the characteristics of a certain group. In Table 3, for example, the MET were calculated using both the individual k and $k = 1$ for all subject separately. In addition, k was assigned 0.93 and 0.66 for male and female subjects, respectively, to identify gender effects. This enables the models of Ma et al. (2009, 2011) be used not only in investigating the individual differences but also in studying the group behaviors of workers.

When using Eq. (5) to determine the MET, it is apparent that the variations of predicted value would be higher when using the individual k as compared to those calculated using a constant k for a group. Variation, due to individual attribute, among a group diminished when k was assigned a same constant for all the individuals in the group. Indeed, when using individual k value for each subject, the MET calculated using Eq. (5) had low correlation coefficients (<0.2) with those of the four other models. This was not unexpected as the individual characteristics of the subject was not considered in the empirical models in the literature (Sato et al., 1984; Rohmert et al., 1986; Mathiassen & Ahsberg, 1999; Garg et al., 2002). When a constant was assigned, either one for all the subjects or one for each gender, the MET calculated using Eq. (5) had high correlation coefficients (0.99 or more) with those of the other four models.

Even with a high correlation between the MET calculated using models from Ma et al. (2009) and the four empirical models compared in the current study, the predicted METs using the former were quite different from those four models. It is known that fatigability depends on posture, and force exertion pattern. Only single arm was tested in the current study while both arms were involved in those of the four studies. In addition, the subjects in the current study were sitting during the test while the subjects in those four studies were standing. The force exertion patterns in the four studies (Sato et al., 1984; Rohmert et al., 1986; Mathiassen and Ahsberg, 1999; Garg et al., 2002) were also different from the pushing in the current study. The applicability of the four empirical shoulder models in the literature in assessing the fatigability in such a task as in the current study, therefore, may be questionable. As a matter of fact, there is no empirical muscular fatigue model established especially based on such a single arm pushing task. The MET model of Ma et al. (2009, 2011), on the other hand, is a theoretical model which hypothesizes only the fact that muscle force decrease when fatigue occurs. This model did not consider specific

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posture or force exertion pattern involved. It is, therefore, believed that the applicability of this model is superior to those empirical models derived specifically under certain posture and force exertion pattern.

5. Conclusion

A single arm pushing experiment, using both male and female subjects, was conducted in an electronic factory. Both the theoretical models in predicting the muscular strength and MET by Ma et al. (2009) were adopted. The results of both the fatigue rate and fatigue resistance indicated that females were more resistant to muscular fatigue than males in the pushing task. This gender difference was consistent with those reported in the literature. The results of the muscular strength prediction show that the predictability of the muscular strength model is acceptable. The prediction errors for muscular strength for female subjects were significantly lower than those of the male subjects. The implication is that the regression approach in determining the fatigability so as to predict the muscular strength after a force exertion may be utilized to assess muscular fatigue in a similar scenario in industrial settings. The accuracy for such assessment for females will be better than those of males. The predicted MET using the model by Ma et al. (2009), with a group constant k, was highly correlated with those using the four empirical models compared in the current study.

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