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Cumulative local muscle fatigue may lead to potential musculoskeletal disorder (MSD) risks, and subject-specific muscle fatigability needs to be considered to reduce potential MSD risks. This study was conducted to determine local muscle fatigue rate at shoulder joint level based on an exponential function derived from a muscle fatigue model. Forty male subjects participated in a fatiguing operation under a static posture with a range of relative force levels (14–33%). Maximum muscle strengths over time were measured after different fatiguing sessions. The time course of strength decline was fitted to the exponential function. Subject-specific fatigue rates of shoulder joint moment strength were determined. Good correspondence ($R^2 > 0.8$) was found in the regression of the majority (35 out of 40 subjects). Substantial inter-individual variability in fatigue rate was found and discussed.

Practitioner Summary: Different workers have different muscle fatigue attributes. Determination of joint-level subject-specific muscle fatigue rates can facilitate physical task assignment, work–rest scheduling, MSD prevention and worker training and selection.

Keywords: static muscular strength; joint strength decline; muscle fatigue rate; subject-specific fatigue rate

1. Introduction

Human intervention is often involved in occupational activities, especially in material handling, assembly and maintenance tasks (Melhorn, Wilkinson, and O'Malley 2001; Melhorn, Wilkinson, and Riggs 2001; Kumar 2001). In these activities, the operator needs sufficient muscle strength to meet force requirement for operating equipment or sustaining external loads. Insufficient strength can lead to overexertion of the musculoskeletal system and to consequent injuries (Armstrong et al. 1993; Chaffin, Andersson, and Martin 1999; Horton, Nussbaum, and Agnew, 2012).

A decrease in muscle strength is often experienced in a physical operation under a sub-maximal force, either in a continuous way or in an intermittent way (Wood, Fisher, and Andres 1997; Yassierli and Nussbaum 2009). This decrease in maximum force output results from different sources, such as muscle fatigue, musculoskeletal disorders (MSDs), lack of motivation and so on. Among these sources, muscle fatigue is one of the most prevalent reasons and is defined as 'any exercise-induced reduction in the capacity to generate force or power output' (Vøllestad 1997). Muscle fatigue exposes operators to more risks of overexertion, and cumulative muscle fatigue may result in MSDs (Armstrong et al. 1993; Chaffin, Andersson, and Martin 1999).

Fatigue progression is closely dependent on task assignment and subject-specific fatigue attributes. Different task parameters (load, duration of exertion, posture and motion, etc.) lead to different fatigue progressions in physical operations (Chaffin 2009; Yassierli and Nussbaum 2009; Enoka 2012). Individual physical attributes (strength, fatigue rates, recovery rates, etc.) can influence the fatigue progression as well. It is believed that fatigue attributes differentiate from each other among operators (Yassierli, Iridiastadi, and Wojcik 2007; Yassierli and Nussbaum 2009; Avin et al. 2010; Avin and Frey Law 2011). Determination of subject-specific fatigue attributes is of interest and of importance for physical work design (Chaffin 2009).

Muscle fatigue progression has been studied mainly from two different approaches. One approach is the maximum endurance time (MET) approach. MET can assess the ability to resist fatigue by measuring the maximal duration while exerting a force at a specific level until failure. A large amount of effort has been contributed to developing MET models for different muscle groups under different static working conditions (Rohmert 1960, 1973; Rohmert et al. 1986; Bishu, Kim, and Klute 1995; Kanemura et al. 1999; Mathiassen and Ahsberg 1999; Garg et al. 2002; Law and Avin 2010). Although the MET models can predict the MET under a given relative force level, the decrease in the muscular strength cannot be

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predicted directly by MET models. Moreover, due to the nature of the formation in those MET models from group data, it is difficult to determine subject-specific fatigue attributes.

Another approach to characterise muscle fatigue progression is to develop muscle fatigue models, and hence to predict the strength decline directly. Some work (Giat, Mizrahi, and Levy 1993; Ding, Wexler, and Binder-Macleod 2000) contributed to complex physiological muscle fatigue models. Those models are able to describe the muscle fatigue progression precisely for a single muscle. However, they are too complex for industrial application due to the difficulty of identifying a great number of parameters in the model.

Some researchers established some fatigue models by conducting fatiguing tasks (Deeb, Drury, and Pendergast 1992; Søgaard et al. 2006; Roman-Liu, Tokarski, and Wójcik 2004; Roman-Liu, Tokarski, and Kowalewski 2005; Iridiastadi and Nussbaum 2006). Among those models, exponential declines in muscular strength are found (Deeb, Drury, and Pendergast 1992; Roman-Liu, Tokarski, and Wójcik 2004; Yassierli, Iridiastadi, and Wojcik 2007). However, the fitting parameters in those exponential functions could not implicate more information about fatigue attributes of each subject.

Some other researchers (Liu, Brown, and Yue 2002; Ma et al. 2009; Xia and Frey Law 2008) have tried other models to describe muscle fatigue progression. Xia and Frey Law (2008) proposed a three-compartment muscle fatigue model based on muscle motor units model in Liu, Brown, and Yue (2002), and they have run simulation to demonstrate fatigue progression under a variety of loading conditions. In this model, fatigue and recovery attributes of different types of muscle fibres were assigned with different values in the simulation. However, the lack of validation limits the application of this model.

Ma et al. (2009) proposed a muscle fatigue model to describe muscle fatigue progression from a macro perspective. In this model, task parameters and muscle fatigue rate are combined together to understand the fatigue caused by tasks and fatigue attributes. Ma et al. (2011) developed an approach to determine fatigue resistances of different muscle groups using this fatigue model. Twenty-four MET models (El ahrache, Imbeau, and Farbos 2006) for different muscle groups can be effectively fitted and explained by this approach. We suggest that this muscle fatigue model is capable of assessing fatigue progression of a muscle group in static cases. Moreover, we found that the muscle fatigue progression of each subject under static cases can be predicted in the form of an exponential function derived from the fatigue model, and one important factor (fatigue rate) in this model emerges to represent the subject-specific muscle fatigue attribute.

Regarding the subject-specific fatigability, some other measures were used to assess muscle fatigability, such as endurance time, electromyography power spectrum (median frequency and median power frequency), mean arterial pressure and so on (Clark et al. 2003; Hunter et al. 2004; Hunter, Critchlow, and Enoka 2005; Yoon et al. 2007; Frey Law and Avin 2010; Côté 2012). However, as pointed out by Vøllestad (1997), the greatest limitation is that these measures measure muscle fatigue indirectly. Therefore, we chose to use the fatigue rate in Ma et al. (2011) to represent inter-individual difference in fatigue progression beyond those limitations.

We conducted this study to verify whether the fatigue progression under a static operation can be well fitted by a specific exponential function derived from the muscle fatigue model and to check whether the fitting parameter (fatigue rate) could represent subject-specific fatigue attributes among different subjects.

2. Subject-specific fatigue rate determination

Ma et al. (2009) proposed a muscle fatigue model in the form of a differential equation (Equation (1)). The muscle fatigue model describes the change of the maximum strength over time. Related parameters and their descriptions are given in Table 1. In this model, the fatigue rate (k) is a parameter to indicate the relative speed of strength decline within a muscle or muscle group.

$$\frac{\mathrm{d}F(t)}{\mathrm{d}t} = -k\frac{F(t)}{\mathrm{MVC}}F_{\mathrm{load}}(t). \tag{1}$$

Table 1. Parameters in the dynamic fatigue model.

Item	Unit	Description
MVC or $F_{\max}$	N	Maximum voluntary muscle strength under non-fatigued state
$F(t)$	N	Maximum voluntary muscle strength at time t
$F_{\mathrm{load}}(t)$	N	External load that the muscle needs to bear
k	min^{-1}	Fatigue rate
%MVC		Percentage of the voluntary maximum contraction
f_{MVC}		%MVC/100, $f_{\mathrm{MVC}} = F_{\mathrm{load}}/\mathrm{MVC}$

In a static muscular operation, $F_{\text{load}}(t)$ keeps constant, and the reduction of the muscular strength can be further predicted by Equation (2). This equation describes the muscle fatigue progression in the form of an exponential function. Three parameters (F_{max}, F_{load} and k) act upon the fatigue progression under a static operation. In general, F_{load} is determined by the task design, and it can be measured or calculated via force analysis, and F_{max} and $F(t)$ can be measured to unfold the muscle fatigue progression. The fatigue rate k is task independent and is influenced by several factors (e.g. muscle fibre-type composition, age and gender) (Ma et al. 2011).

$$\frac{F(t)}{F_{\text{max}}} = \mathrm{e}^{-kf_{\text{MVC}}t}. \tag{2}$$

According to the definition of muscle fatigue, muscle fatigue progression can also be described by measuring the maximum muscle strengths over time during a fatiguing operation. If the same muscle progression can be depicted using both ways, it will suggest that parameter k could be determined using the muscle fatigue model. Therefore, it is essential to verify whether the fatigue progression of each subject under a static fatiguing operation follows an exponential function in the form of Equation (2) with a high coefficient of determination R^2.

Suppose that we have already a set of real measurements for a given static operation, where F_{t_i} indicates the maximum strength $F(t)$ at time instant t_i. At the beginning of a physical task, the subject is supposed having no muscle fatigue. Therefore, $F_{t=0}$ can be treated as the maximum voluntary contraction (MVC) F_{max}. Equation (2) can be further transformed into Equation (3).

$$\frac{\ln(F_{t_i}/\text{MVC})}{f_{\text{MVC}}} = -kt_i. \tag{3}$$

Since F_{load} and MVC are measured and/or known, fatigue rate k can be further determined by linear regression. A high goodness of fit between maximum strengths over time and the exponential function would suggest the usefulness of the fatigue rate. The goodness of fit is assessed by the R^2 value in a linear regression without an intercept.

3. Materials and methods

3.1 Subjects

Since the focus of this study is on manufacturing and assembly and the majority of the operators are male workers, 40 right-handed male industrial workers participated in the experiment after signing a written informed consent. Age, stature, body mass, upper limb anthropometry data and body mass index (BMI) were recorded or measured upon arrival at the laboratory (see Table 2). Participation was limited to individuals with no previous history of upper limb disorders. Ethical approval for this study was obtained in advance.

3.2 Task design

In this study, a typical overhead drilling operation under laboratory conditions was used to measure muscle fatigue progression at shoulder joint level (see Figure 1). This task was simplified from a real drilling operation defined from a research programme of the European Aeronautic Defence and Space (EADS). This operation was selected as a typical task because there are a few ergonomics problems (Melhorn, Wilkinson, and O'Malley 2001). A heavy external load demands great physical strength to hold a machine and maintain the operation for a certain period, and local muscle fatigue occurs rapidly in upper limb and lower back. MSD risks can be increased by force overexertion and sustained vibration while drilling.

Table 2. Subject physical characteristics.

Characteristic	Mean	SD	Maximum	Minimum
Age (year)	41.2	11.4	58	19
Height (cm)	171.2	5.1	183.0	160.0
Mass (kg)	70.2	10.4	95.0	50.0
Upper arm (cm)	23.6	3.0	31.0	16.0
Lower arm (cm)	25.6	1.8	29.0	22.0
BMI	23.9	3.35	31.1	18.7

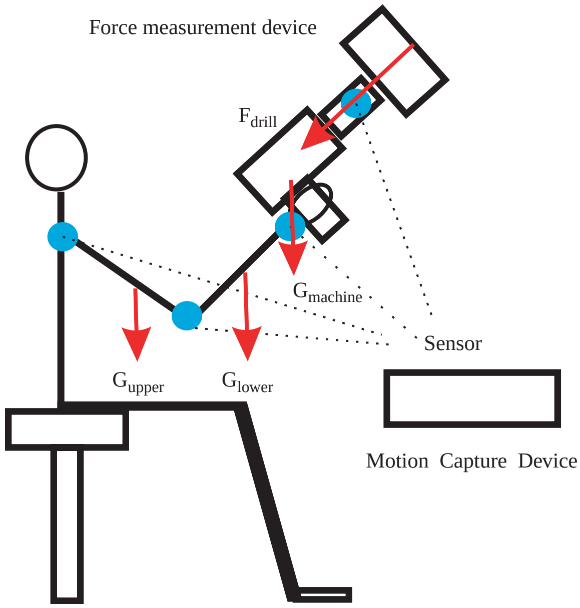

Figure 1. Seated static posture in the experiment and materials used in the experiment. F_{drill}, drilling force; G_{machine}, the weight of the drilling machine; G_{upper}, the weight of the upper arm; G_{lower}, the weight of the lower arm.

The magnitude of the external load and the duration of the operation are two key factors to simulate the real situation. The relative load needs to be adjusted so that subjects can both experience fatigue and can also endure the operation for a certain period. In this case, according to the strength model in Chaffin, Andersson, and Martin (1999) and the MET models in El ahrache, Imbeau, and Farbos (2006), a subject must apply a drilling force of 25 N and hold a drilling machine with a mass of 2.5 kg. The drilling force is only applied along the drilling direction towards the subject. The estimated moment generated by the external load (including the weight of the arm) is about 33% of the shoulder joint flexion strength of a 50th percentile male and the endurance time under this load is estimated around 4 min.

3.3 Measures

In this study, shoulder joint moment strength was used to describe fatigue progression and measure the maximum force output in the drilling direction to estimate shoulder joint moment strength (see Figure 2).

It is assumed that the measured force is generated by joint moment strength of the right upper limb. Shoulder joint and elbow joint have similar strength profiles according to the joint moment strength models (Chaffin, Andersson, and Martin 1999), and shoulder joint has higher fatigability in MET models than elbow joint (Frey Law and Avin 2010). Furthermore, it is obvious that shoulder joint is charged with a much larger moment load than elbow joint in this drilling case. Therefore, the bottleneck for the output strength is shoulder joint.

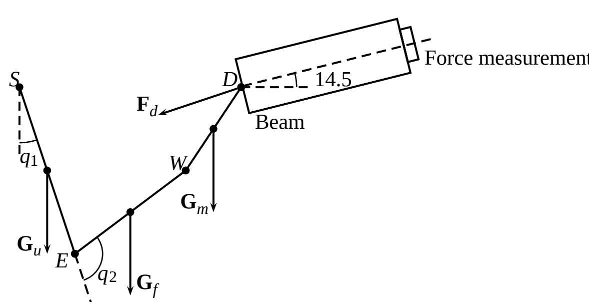

Figure 2. Force schema in the drilling operation. S, shoulder; E, elbow; W, wrist; D, drilling point. $\boldsymbol{F}_{\text{d}}$, drilling force applied to the upper limb; $\boldsymbol{G}_{\text{m}}$, weight of the drilling machine; $\boldsymbol{G}_{\text{u}}$, weight of the upper arm; fG_{f}, weight of the forearm; q_1, flexion of the upper arm and q_2, flexion of the elbow.

The moment load in shoulder joint can be approximately estimated by Equation (4) (see Figure 2). The mass and the centre of gravity of each body segment were estimated from the anthropometry database (Chaffin, Andersson, and Martin 1999).

$$\boldsymbol{\Gamma}_{\text{load}} = \left(\frac{\mathbf{s}-\mathbf{e}}{2}\right) \times \mathbf{G}_{\text{u}} + \left(\frac{\mathbf{w}+\mathbf{e}}{2} - \mathbf{s}\right) \times \mathbf{G}_{\text{f}} \quad + \left(\frac{\mathbf{d}+\mathbf{w}}{2} - \mathbf{s}\right) \times \mathbf{G}_{\text{m}} + (\mathbf{d}-\mathbf{s}) \times \mathbf{F}_{\text{d}}, \tag{4}$$

where $\mathbf{s} = (s_x, s_y, s_z)^\top$, $\mathbf{e}$, $\mathbf{w}$ and $\mathbf{d}$ represent the coordinates of the positioning sensors attached to the shoulder (S), elbow (E), wrist (W) and drilling contact point (D), respectively. In this experiment, since the subject's arm is strictly limited within the sagittal plane, only the force within this plane was measured and used to calculate the torque.

Since joint moment strength was used in this study, the fatigue model in Equation (1) can be changed to Equation (5) by replacing all of the force terms with joint moment terms.

$$\frac{\mathrm{d}\Gamma(t)}{\mathrm{d}t} = -k\frac{\Gamma_{\text{load}}(t)}{\Gamma_{\max}}\Gamma(t). \tag{5}$$

Under this simplified case, Γ_{load} can be determined by force analysis, and f_{MVC} can be calculated from data analysis by normalising Γ_{load} over $\Gamma_{\max}$. Γ_{t_i} is a joint maximum strength over time, and it can be estimated by measuring the maximum force F_{t_i} in the drilling direction.

3.4 Material

In the experiment, a dynamometer was used to measure the drilling force in the drilling direction (see Figure 1). The dynamometer measures the pressing force perpendicular to the load cell surface with a measurement range upto 300 N and a precision of 1 N. A magnetic motion capture device FASTRAK® (POLHEMUS, Inc., Colchester, USA) was used to capture the upper limb posture in the experiment. As shown in Figure 1, four positioning sensors were attached to the key joints of the upper limb and the drilling machine. The Cartesian coordinates of the shoulder, the elbow, the wrist and the contact point between the drilling machine and the work piece were captured. The tracking device runs at 30 Hz per sensor and has a static positioning accuracy of 1 mm. The recorded coordinates of each tracker were used to reconstruct the posture of the worker in post-experiment analysis.

A wooden beam with a mass of 10 kg was used to provide the drilling force. Wooden material was used to avoid magnetic distortions caused by ferrous material and to ensure motion capture accuracy. The wooden beam was suspended with an inclination angle between the beam and the horizontal line of 14.5°. During operation, the subject had to push the beam against the force measurement device and hold it for a certain period. According to the force analysis of the pendulum, a tangential force of 25 N was charged to the upper limb. Before each trial, this external load was calibrated to ensure that there was exactly a force of 25 N applied in the drilling direction. The weight of the drilling machine with a drilling tool made of concrete (also to avoid magnetic distortions) was 2.5 kg.

3.5 Experiment procedure

Each subject had to complete 10 sessions: one MVC session and nine fatiguing sessions.

In the MVC session, MVC was determined as the greatest exerted force in the drilling direction over three trials. In each trial, subjects were verbally encouraged to maintain the maximum peak force for 3 to 5 s. The measured MVC was also denoted as F_0 to represent the subject's initial maximum strength at the beginning of the operation. Between each trial, subjects were asked to take at least 5 min rest until self-reported full recovery (Chaffin, Andersson, and Martin 1999).

There were nine fatiguing sessions with different time intervals (15, 30, 45, 60, 75, 90, 120, 150 and 180 s). The sequence to complete these nine sessions was randomly assigned for each subject. In each fatiguing session, the subject was asked to hold the constant external load for the time interval t_i (e.g. 30 s). After that, the muscle strength over time F_{t_i} (e.g. F_{30}) was measured by asking the subject to exert maximal voluntary strength with a peak force for 3 to 5 s. After measurement, subjects took rest for at least 5 min or even longer until self-reported total recovery.

After recovery from a fatiguing session, the subject was asked to conduct an MVC test randomly. Each subject conducted the MVC test at least three times for nine fatiguing sessions. Full recovery would be recognised if the measured maximum strength in this test was more than 95% of the measured MVC in the MVC session. Otherwise, the subject would be asked to take a longer break until full recovery. Once the subject reported that he could not sustain the operation within the session, the experiment would be stopped immediately to avoid injuries.

Within each session, the subject was seated upright, and the right shoulder was fixed to a shoulder support against the wall to restrict the movement of the shoulder and to decrease the engagement of the lower back. The left upper limb was free, and the right upper limb was limited in the sagittal plane by position constraints. The position constraints provided posture references to the subject to maintain initial posture as well as possible, but provided no support to the upper limb. The seated height and location were adjusted according to subjects' height and upper limb length to reduce variability among the different subjects.

3.6 Data analysis

The objective of this analysis was twofold.

(1) To test whether fatigue progression of each subject in shoulder joint maximum strength can be well fitted by the exponential function derived from the muscle fatigue model.
(2) To analyse the relationship between muscle fatigue rate and joint moment strength.

For the first objective, muscle fatigue progression of each subject was fitted with the exponential function (Equation (3)). The coefficient of determination of each fitting was recorded for each subject and analysed. For the second objective, two groups of subjects were selected to assess the relationship between joint moment strength and joint fatigue rate. Since muscles engaged in the action mainly determine the maximum joint strength and we assumed that determinant muscle-related factors for muscle strength could probably act effects on muscle fatigue rate as well. One group (Group A) has subjects with 10 highest joint moment strengths; another group has subjects with 10 lowest joint moment strengths. Besides joint strength, some other measures (e.g. BMI and age) may also influence fatigue rate. Correlations between fatigue rate and other measures were also statistically analysed. SPSS was used to do all the statistical analyses and fitting.

4. Results

4.1 Fatigue progression

Joint moments of each subject were normalised over the estimated maximum moment strength. Then the normalised values were fitted using Equation (3) to calculate the fitting coefficient R^2 and to determine the fatigue rate. The statistical results of R^2 of the regression and the fatigue rate k are listed in Table 3, and the histograms of R^2 and k are shown in Figures 3 and 4, respectively.

Table 3. Statistical analysis of fatigue rate k.

Item	Mean	SD	Minimum	Maximum
Joint moment strength (Nm)	45.1	7.4	67.4	32.1
k	1.02	0.49	0.37	2.29
R^2	0.87	0.14	0.23	0.99

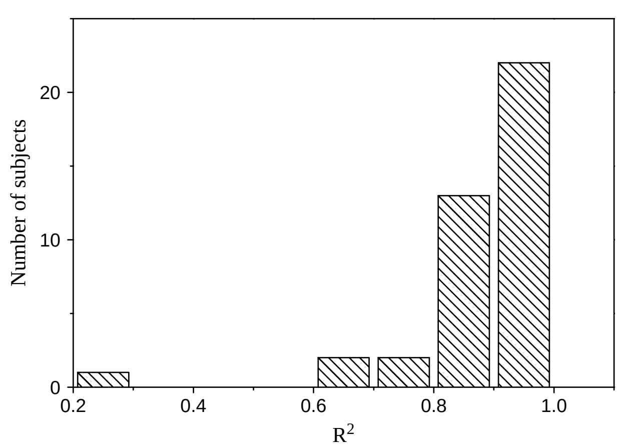

Figure 3. Histogram of coefficient of determination R^2.

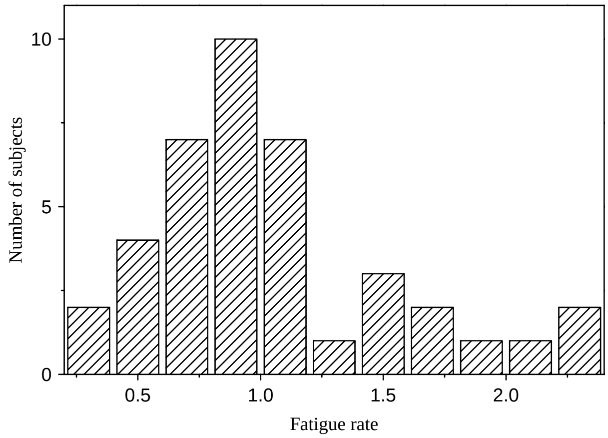

Figure 4. Histogram of fatigue rate at shoulder joint.

Thirty-five out of 40 subjects had a high coefficient of determination R^2 over 0.8 in joint moment regression. Four out of the other five subjects had a fair coefficient R^2 over 0.63, and only one of the five subjects had a very poor R^2 (0.23).

4.2 Relationship between fatigue rate and joint maximum strength

A pair-wise correlation matrix was determined between joint moment fatigue rate, joint moment strength, age and BMI. The results are shown in Table 4. It was found that joint moment strength is strongly correlated with fatigue rate ($p < 0.05$), while no strong correlations were found in the pair of fatigue rate and BMI and the pair of fatigue rate and age.

No significant differences were found between two groups in age [Group A: 42.9 (standard deviation, SD = 7.4); Group B: 39.1 (SD = 15.4), $p = 0.49$] and BMI [Group A: 24.9 (SD = 2.4); Group B: 25.2 (SD = 4.2), $p = 0.78$]. Significant differences ($p < 0.001$) were found in joint maximum strength between Group A [mean = 60.8 Nm (SD = 4.7 Nm)] and Group B [mean = 37.7 Nm (SD = 3.3 m)].

Table 5 shows the difference of fatigue rates between different groups with use of *t*-test. The subjects with higher strength have significantly higher fatigue rate even though the relative load is smaller than the subjects with lower strength.

4.3 Posture change during the drilling operation

The posture of upper limb during the drilling operation was calculated from the motion data. Because the arm was constrained in the sagittal plane, only the flexion angles of the shoulder joint and elbow joint were calculated to represent

Table 4. Correlation matrix for study variables.

	Fatigue rate	BMI	Joint moment strength	Age
Fatigue rate	1	−0.09	0.616*	0.033
BMI		1	0.09	0.40*
Joint moment strength			1	0.072
Age				1

*$p < 0.05$.

Table 5. Effect of muscle strength on fatigue rate.

Group	Mean	SD	t	p value
k				
A	1.47	0.53	4.628	0.0001
B	0.64	0.20		

Table 6. Posture change during the experiment (°).

Time (s)	0	15	30	45	60	75	90	120	150	180
Elbow										
Mean	50.1	53.1	55.1	55.1	57.5	59.9	59.9	64.2	66.7	75.5
SD	16.1	15.4	15.0	15.7	16.4	19.0	19.2	19.9	21.3	21.9
Shoulder										
Mean	46.4	44.5	43.6	44.2	42.8	42.1	41.9	39.7	37.5	30.5
SD	16.2	15.0	14.6	15.2	14.7	16.6	17.0	16.6	17.9	17.3

arm posture to eliminate influence from different limb lengths. The statistical results of elbow flexion and shoulder flexion angles across participants were calculated and are shown in Table 6. The posture change during the working process is shown in Figure 5. The changes in the posture followed the following tendency: the greater the fatigue was, the closer the upper limb was to the trunk. In this way, the moment produced by the mass of the upper limb around the shoulder joint could be reduced.

5. Discussion

5.1 Muscle fatigue progression

In this study, it was found that the fatigue progression at the shoulder joint among most of the subjects (35/40) can be well fitted ($R^2 > 0.8$) by the muscle fatigue model. Five out of 40 subjects were found with low R^2 coefficients.

There are some reasons leading to those relatively poor fittings. First, the motivation and the attitude of the subject during the experiment could potentially influence the result. Second, even though the posture of the arm was strictly constrained in the sagittal plane, subjects could still have a certain degree of mobility. The willingness to maintain the posture may have influenced the muscle recruitment strategy, muscle coordination and posture during the experiment. Third, weak muscular strength could probably lead to poor fitting performance indirectly. The subjects with $R^2 = 0.23$ had the second lowest MVC among the 40 subjects. Lower muscle strength means relatively higher physical workload during the experiment and higher demand to maintain posture, and hence static operation would be harder to maintain.

Fatigue may occur at any step along the pathway that is involved in muscle contraction (Berne et al. 2004). Both metabolic factors within the muscle and the impairment of activation could contribute to the decline in muscle power output (Chaffin, Andersson, and Martin 1999; Allen, Lamb, and Westerblad 2008). In a physical operation, muscle fatigue progression could be influenced by physical task, motivation and individual fatigue attributes. However, under static operation and effective verbal encouragement, the influences from motivation could be rather limited. Therefore, muscle fatigue progression was probably mainly caused by relative loads and subject-specific fatigue attributes in this study.

The fatigue model (Equation (2)) is formed from a macro perspective and can be explained based on motor-unit principle from a micro perspective (Ma et al. 2009). The product of relative load and fatigue rate determines the decline of

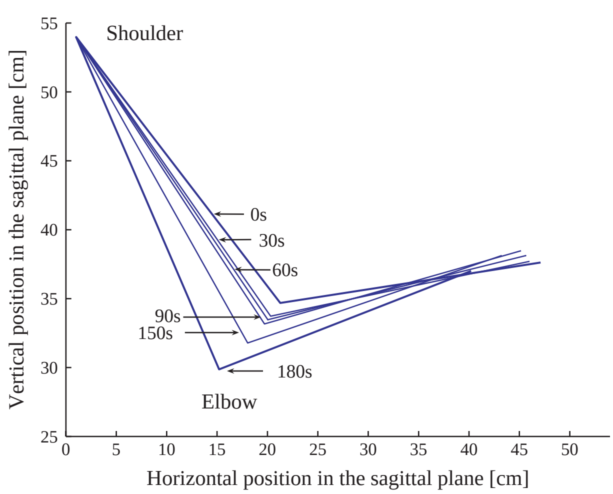

Figure 5. Posture change during the drilling operation (mean values across participants).

muscle strength. According to muscle physiology, fatigue rate can be recognised as a parameter to represent the overall fatigue resistant performance of a muscle group at joint level under a specific task (Ma et al. 2011).

We selected this model to determine fatigue attribute for the following reasons: (1) in comparison to Deeb's model (Deeb, Drury, and Pendergast (1992)), this model enables us to decouple relative load and the subject-specific attribute; (2) muscle fatigue rate can be influenced by muscle composition, neuromuscular activation patterns and coordination among single muscles; therefore, the fatigue rate in this model could cover more effects of influencing factors than the fatigue rates of different types of muscle fibres in Xia and Frey Law (2008); (3) this model is less complex than the three-compartment model in Xia and Frey Law (2008), and it could be more practical for industry application.

5.2 *Subject-specific fatigue rate*

It was found that there are substantial differences among different subjects in fatigue rates at the shoulder joint level. It suggests that the fatigue rate k can be used to characterise different fatigue attributes among subjects at the shoulder joint level under this specific fatiguing condition.

The underlying mechanisms for those differences in fatigue rate are very complex. Physiologically, differences in fatigue rates are mainly caused by four factors: (1) muscle strength (muscle mass) and associated vascular occlusion, (2) substrate utilisation, (3) muscle composition and (4) neuromuscular activation patterns (Hicks, Kent-Braun, and Ditor 2001; Ma et al. 2011). At the same time, demographic parameters (age and gender) and their interactions can lead to changes in muscle composition as well (Mademli and Arampatzis 2008; Yassierli and Nussbaum 2009). In addition, personal working experience or physical exercises and living style can also change the muscle strength and endurance via the adaptive response of muscle cells to regular external loads (Berne et al. 2004; Wüst et al. 2008). All these factors generate effects together on subject-specific fatigue attributes.

It was also found that fatigue rates are positively correlated to maximum joint moment strength in this study, even though the relative loads for the subjects with higher strength were lower. Between-subject differences in the ratio of type I muscle fibres (slow twitch and more fatigue resistant) to type II muscle fibres (fast twitch and less fatigue resistant) might explain the differences in fatigue rates. Muscle strength depends strongly on muscle fibre size and muscle fibre composition (Fitts, McDonald, and Schluter 1991). Subjects in Group A and Group B did not have significant differences in BMI and age, which implicates that the strength differences were probably not mainly caused by muscle mass or muscle fibre size or age-related factors. It could be concluded that the strength differences were caused by different compositions of muscle fibre types. Subjects with higher strengths could probably have a higher proportion of type II muscle fibres and lower proportion of type I muscle fibres. This leads to higher joint moment strength and faster fatigability in the muscle.

No significant correlation between fatigue rate and age and between fatigue rate and BMI was found. Regarding the age effect, the subjects were not strictly controlled to two age groups. The subjects in this experiment were in their young age or middle age, which might not be enough to reveal the aging effect. Regarding BMI, most of the subjects were in the normal weight and overweight group. Only a few subjects belong to Class I obesity or underweight category.

5.3 *Posture change*

Although posture references were provided to avoid mismatches in different test trials, it was still very difficult for subjects to maintain the purely static posture during the operation. Small changes occurred in the experiment, but those changes did not generate excessive variation in joint strength. In this case, the variation of the maximum joint moment strength is no more than 3% relative to the maximum strength under the initial posture according to the joint moment strength model (Chaffin, Andersson, and Martin 1999). The change of the joint strength due to posture change might lead to change of relative strength. So the sensitivity of the change was checked, and it was found that the changed maximum joint strength would lead to no more than 4% change of the relative strength ($4\% f_{\mathrm{MVC}}$), which was acceptable in this case.

Several reasons may cause posture change in the experiment. Fatigue might be one of these reasons. Changes in the posture can be explained by a global posture control strategy, which includes decreasing the joint loads in the operation by moving the upper limb closer to the body; a similar finding has been reported by Fuller et al. (2008). This change would influence joint strength (Roman-Liu and Tokarski 2005; Anderson, Madigan, and Nussbaum 2007). Besides fatigue, there were still other error sources leading to change of posture. First, the actual posture was determined by the anthropometry of different subjects. Different arm lengths could cause potential differences in elbow flexion and shoulder flexion. Second, the posture was calculated from the position sensors attached to the key joints. Each subject might have different sensor configurations, which might lead to calculation errors. Third, there might be differences among the postures that each subject took in different fatiguing sessions.

5.4 Limitations

There are several limitations in this study. First, the focus of the present study was on the fatigue effect in static industrial operations in a continuous working process. Recovery effect was not taken into consideration in this study. Second, this study was conducted under a simplified overhead drilling operation, and the conclusion drawn from this study has a strong task dependency. A simplified overhead drilling operation decreases the reliability of applying the findings into other tasks in industry. Some other MSD causes such as vibration (Kattel and Fernandez 1999) were neglected in this study. Third, the force analysis in this study is available only for a static case. In a real operation, the motion involved in the operation could result in a different dynamic workload. Moreover, only fatigue with the relative force falling from 14% to 33% (mean = 24.3%, SD = 4.4%) of the specific job operation was tested, so the result is available only for similar physical operations. Last but not the least, the fatigue progression was measured under static isometric contraction, and the results could not be extended to dynamic or intermittent fatiguing tasks.

6. Conclusions and perspectives

This paper provides an experimental approach to determine subject-specific fatigue rate at the shoulder joint level. Fatigue progression in a simplified static drilling operation was measured and analysed using an exponential muscle fatigue model. Muscle fatigue progression in joint moment strength could be well fitted by the fatigue model ($R^2 > 0.8$). This result suggests that the muscle fatigue model could be used to describe fatigue progression for industrial operations within the range of 14–33% of the relative submaximal level under static cases. Different fatigue rates among subjects could be used to characterise the individual fatigue attributes under the same workload. Determination of subject-specific fatigue rates could be useful for physical task assignment, worker training, worker selection and work design.

Since fatigue rate is important and could be influenced by a number of factors, further study would be necessary to find the effects of these influencing factors (Côté 2012). Gender difference, age difference and joint difference in fatigue rates could be investigated. Static continuous and dynamic intermittent tasks could be investigated under different relative load levels.

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