Work Efficiency Model Based on Posture in Horizontal Drilling Task

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Abstract

Uncomfortable posture may not contribute only to the development of musculoskeletal disorders (MSDs) but also to the loss of energy and the decrease in work efficiency (WE). Measuring WE based on activity energy expenditure (AEE) have not got much attention in work places. The study aims to develop a model of work efficiency (WE) based on body posture for performing horizontal drilling tasks. Ten subjects, all men with an average age of 23.3 ± 0.67, participated in the experiment. Six coordinated postures of shoulder and trunk flexion were tested. Activity Energy Expenditure (AEE) and Work Efficiency (WE) were the dependent variables. Repeated measures ANOVA were used to analyze the data. The findings showed that statistically significant trends (P <0.01) of increasing AEE while the trunk and shoulder move away from the neutral posture. Overall, these results provide valuable insights into assessing WE on the basis of the AEE and the activity wasted energy (AWE) due to unproductive movements while standing in difficult postures, taking the neutral posture as a zero reference of wasted energy.

Keywords: Activity Energy Expenditure (AEE), Activity Wasted Energy (AWE), Posture, Work Efficiency (WE).

INTRODUCTION

The use of manual handling tools is widely used in the maintenance, power engineering, automobile assembly, electricity works, construction, healthcare, and farming industries. Musculoskeletal disorders (MSDs) such as upper limb pain (ULP) and low back pain (LBP) are the most common work-related injuries in manual handling tasks. Such diseases are mainly caused by over-exertion or repetitive or prolonged poor working postures during performing tasks [1]. In a recent investigation on Malaysian industrial workers by Zein et al. [2], it was found that the most challenging postures practised by Malaysian industrial workers are moderate bending forward trunk and shoulder flexion at the chest level. These critical backgrounds in aforementioned studies above make a more consideration that working in the uncomfortable posture not only contribute to the development of MSDs but also result in the loss of body energy and work efficiency (WE).
BACKGROUND OF STUDIES

Posture

Existing literature on posture is extensive, focuses mostly on subjective assessment and overlooks the effect of combining different postures [3]. Many studies agreed that shoulder/elbow flexion and trunk bending forward have the significant impact on physiological demands and subjective perception [4-8]. However, these studies have conflicting results regarding the produced stress amount by different coordinated postures. In more details, in a study of Kong et al. [3] showed that back and shoulder flexion angles of 45° are the least discomfort regarding of it’s coordinated postures. Also, Lee [9] reported that postures with shoulder/elbow flexion angle 0/90° have the most excellent holding capability.

Moreover, Sasikumar and Lenin [10] observed that physiological stress is highest while drilling by the extended forearm and above shoulder level. Brookham et al. [11] found that the combination of 60° shoulder flexion and -45° hand internal rotation is the excellent posture.

Energy expenditure

Estimating the energy of physical activity by monitoring the heart rate (HR) is common, reasonably inexpensive and easy to use. Energy is measured by monitoring the HR according to the assumed linear relationship between HR and oxygen consumption [12]. Using heart in low and moderate activity has some drawbacks because it is affected by many factors, such as stress, and caffeine. Therefore, enhancements can be reached by estimating Activity’s energy expenditure (AEE) by merging body posture, body vertical acceleration, whole body acceleration and HR data when compared to using HR or accelerometry data alone [13-15].

There are relatively few historical studies in the area of the relationship between posture, work rate and energy expenditure. Benden et al [16] conducted a study on the use of classroom furniture in three central-Texas elementary schools and used a standing-desk intervention. The results showed that posture has a significant effect on energy expenditure. Also, Nur et al. [17] studied the effects of energy expenditure rate on work productivity performance at different levels of production standard time. They found that energy expenditure rate increases, whereas targeted productivity decreases at hard and very hard production standard time.

Efficiency

Efficiency is correctly doing work in the context of physical and cognitive health. Ergonomists are concerned with physical activities to maximize individual job performance and minimize energy expenditure during physical tasks [18]. In some tasks, energy is wasted because of unproductive activities such as static exertion, awkward postures, lack of work breaks and inefficient use of equipment or methods. These unproductive movements lead to decrease efficiency and productivity [19]. A large and growing body of literature has focused on the study of WE which equal the work done (In joules or calories) over the metabolic energy allocation in the body during sports and physical work activities [20-24]. Work done is the summation of external work performed by the centre of body mass on the environment, and internal work is due to the movement of internal body parts around the centre of body.
mass [25]. Force plates can be used for assessing all the work done, but its use is limited to earth connection [26]. Also, ergometers can be used for measuring work done in some activities, such as treadmill sports machine and bicycles. Measuring work done has been criticised for its accuracy, and it is challenging to be used in different tasks. Ettema and Lorås [27] noted that efforts for the evaluation of the efficiency of whole-body muscles are unproductive. In the same context, Neptune et al. [28] revealed that considering the efficiency of muscles to represent motion efficiency is inappropriate.

While work done is complicated and cannot be measured in many activities, the energy cost of the whole-body is reasonable can be clearly assessed. Furthermore, since the possibility to efficiently consume metabolic energy to do work is a crucial factor for performance survival [29], Therefore, WE can be increases with the reduction of activity’s wasted energy (AWE) due to unproductive movements. Thus, the aims of this research are 1) to investigate how forward trunk bending and shoulder flexion (as main or interaction effects) will affect AEE in horizontal drilling task and 2) to develop a model to predict WE on the basis of AEE and AWE in six coordinated postures of shoulder and trunk.

MATERIAL AND METHODS

Subjects

Ten men participants with demographic information as shown in Table 1 were selected to carry out the experiment. All the participants were informed on how to use the tools for the experiment.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Weight (kg)</th>
<th>Height (cm)</th>
<th>Palm width (cm)</th>
<th>Age (year)</th>
<th>Elbow height (cm)</th>
<th>BMI Kg/m²</th>
<th>LBM (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>63</td>
<td>171</td>
<td>8</td>
<td>24</td>
<td>109.5</td>
<td>21.55</td>
<td>49.16</td>
</tr>
<tr>
<td>2</td>
<td>60</td>
<td>164</td>
<td>8</td>
<td>23</td>
<td>104.5</td>
<td>22.31</td>
<td>45.8</td>
</tr>
<tr>
<td>3</td>
<td>73</td>
<td>183</td>
<td>10</td>
<td>23</td>
<td>103</td>
<td>21.8</td>
<td>56.51</td>
</tr>
<tr>
<td>4</td>
<td>58</td>
<td>163</td>
<td>8</td>
<td>23</td>
<td>115</td>
<td>21.83</td>
<td>44.80</td>
</tr>
<tr>
<td>5</td>
<td>67</td>
<td>170</td>
<td>8</td>
<td>23</td>
<td>106.5</td>
<td>23.18</td>
<td>50.13</td>
</tr>
<tr>
<td>6</td>
<td>72</td>
<td>169</td>
<td>8</td>
<td>23</td>
<td>106.8</td>
<td>25.21</td>
<td>51.43</td>
</tr>
<tr>
<td>7</td>
<td>70</td>
<td>166</td>
<td>9</td>
<td>25</td>
<td>104</td>
<td>25.4</td>
<td>49.76</td>
</tr>
<tr>
<td>8</td>
<td>79</td>
<td>170</td>
<td>8</td>
<td>23</td>
<td>107</td>
<td>27.34</td>
<td>54.07</td>
</tr>
<tr>
<td>9</td>
<td>65</td>
<td>174</td>
<td>8</td>
<td>23</td>
<td>109</td>
<td>21.47</td>
<td>50.83</td>
</tr>
<tr>
<td>10</td>
<td>66</td>
<td>172</td>
<td>8</td>
<td>23</td>
<td>107.7</td>
<td>22.31</td>
<td>50.48</td>
</tr>
<tr>
<td>Mean</td>
<td>67.3</td>
<td>170.2</td>
<td>8.3</td>
<td>23.3</td>
<td>107.3</td>
<td>23.24</td>
<td>50.3</td>
</tr>
<tr>
<td>STD</td>
<td>6.03</td>
<td>5.4</td>
<td>0.64</td>
<td>0.64</td>
<td>3.3</td>
<td>1.93</td>
<td>3.26</td>
</tr>
</tbody>
</table>

BMI=Body mass index; LBM=Lean body mass

Apparatus

Actiheart Monitor (AH) (Cambridge Nuro-technology, Cambridge, UK) and drill machine (Bosch: GSR 120-LI Professional) were used in the experiment. Actiheart Monitor is a compact device equipped with an omnidirectional accelerometer and ECG signal processor.
The device is frequently used for recording HR and movement to increase the accuracy of energy expenditure calculation. Acceptable reliability and validity have established from many studies for measuring AEE in the running, walking for children and adults, and in physical activities from low to moderate-intensity in adults [15, 30-32]. Activity level and HR are simultaneously recorded by AH, and data are directly transmitted to the AH’s software. Validated branched equation model is used for estimating AEE for every epoch [14, 30, 33]. The AH has two clips, which are affixed directly to standard ECG electrodes. Typically, one electrode is connected to V1 or V2 (4th intercostals), and another electrode is positioned nearly 10 cm on the other side at V4 or V5. The position can be adjusted to be comfortable for the participant as in Figure 1.

![Location of Actiheart electrodes](image)

**Figure 1. Location of Actiheart electrodes (one of subjects in this research’s experiment).**

**Task description**

First, each participant did lie down on the floor to record the ten minutes of HR’s average. Then the sleeping’s HR (SHR) was determined by using Equation 1 [13, 34].

\[ \text{SHR} = 0.83 \times \text{HR}_{\text{lying}} \]  

(1)

Then, the participant assumed the first posture shown in Table 2 and started drilling the specified line of holes (30 holes × 6 mm as one work stage) on vertical plywood, as in Figure 2-A. In between one hole and another and within the same work stage, the participant was returning his hand down for 2 seconds, as in Figure 2-B, until he finished drilling all the holes. A break of 5 min was taken between the work stages such that to let the HR return to the basal level. Then, the participant changed to the next work stage using another posture, performing the same procedure and the steps as mentioned above until he finished all six stages.

**Variables Identification**

The independent variables are shoulder flexion angles (0°, 45°, and 90°) and Trunk flexion angles (0° and 20°). The dependent variable is AEE consumed by each participant for each work stage of drilling 30 holes (Only the energy consumed during a work stage. Energy
consumed during rests between work stages was excluded). The Controlled variables are: the
diameter of the hole was 6 mm, the material to be drilled was poly wood and the
environmental condition was at room temperature with normal humidity.

Table 2. Coordinated postures of shoulder and trunk flexion.

<table>
<thead>
<tr>
<th>Posture (Work stage)</th>
<th>Interaction Level</th>
<th>Name of variable in SPSS</th>
<th>Flexion angles (shoulder, trunk)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(1,1)</td>
<td>S0T0</td>
<td>(0°,0°)</td>
</tr>
<tr>
<td>2</td>
<td>(1,2)</td>
<td>S0T20</td>
<td>(0°,20°)</td>
</tr>
<tr>
<td>3</td>
<td>(2,1)</td>
<td>S45T0</td>
<td>(45°,0°)</td>
</tr>
<tr>
<td>4</td>
<td>(2,2)</td>
<td>S45T20</td>
<td>(45°,20°)</td>
</tr>
<tr>
<td>5</td>
<td>(3,1)</td>
<td>S90T0</td>
<td>(90°,0°)</td>
</tr>
<tr>
<td>6</td>
<td>(3,2)</td>
<td>S90T20</td>
<td>(90°,20°)</td>
</tr>
</tbody>
</table>

Figure 2. Repetitive cycle movements (one of subjects in this research’s experience).

Data analysis

Repeated measures ANOVA (Variances in means) in SPSS statistical software program
was used for the analysis of AEE collected on the basis of the factors of shoulder and trunk
postures. In repeated measures ANOVA, a big saving in sample size and power can be
achieved. If the sample size is less than 30, the normally distributed of the underlying
population is important. If the sample size is more than 30, the normally distributed can be
ignored [35, 36]. The sample size was calculated using G*power software [37, 38]. Since the
sample size in this research was ten (10), the normality of data is required. The P values in the
Shapiro-Wilk tests of standardized residuals of AEE was > 0.05 as shown in Table 3,
indicating that AEE is approximately normally distributed. The Shapiro-Wilk Test is more
appropriate for small sample sizes. Also, all factors assumed sphericity in Mauchly’s Test (P >
0.05) as shown in Table 4.
Table 3. Tests of normality for AEE.

<table>
<thead>
<tr>
<th>Standardized Residual for</th>
<th>Shapiro-Wilk Statistic</th>
<th>df</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>S0T0</td>
<td>.865</td>
<td>10</td>
<td>.087</td>
</tr>
<tr>
<td>S0T20</td>
<td>.724</td>
<td>10</td>
<td>.002</td>
</tr>
<tr>
<td>S45T0</td>
<td>.928</td>
<td>10</td>
<td>.430</td>
</tr>
<tr>
<td>S45T20</td>
<td>.942</td>
<td>10</td>
<td>.581</td>
</tr>
<tr>
<td>S90T0</td>
<td>.892</td>
<td>10</td>
<td>.178</td>
</tr>
<tr>
<td>S90T20</td>
<td>.859</td>
<td>10</td>
<td>.074</td>
</tr>
</tbody>
</table>

Table 4. Mauchly’s Test of Sphericity of AEE.

<table>
<thead>
<tr>
<th>Within Subjects Effect</th>
<th>Mauchly’s W</th>
<th>Approx. Chi-Square</th>
<th>df</th>
<th>Sig.</th>
<th>Epsilonb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shoulder</td>
<td>.907</td>
<td>.781</td>
<td>2</td>
<td>.677</td>
<td>.915</td>
</tr>
<tr>
<td>Trunk</td>
<td>1.000</td>
<td>.000</td>
<td>0</td>
<td>1.000</td>
<td>1.000</td>
</tr>
<tr>
<td>Shoulder * Trunk</td>
<td>.949</td>
<td>.418</td>
<td>2</td>
<td>.811</td>
<td>.952</td>
</tr>
</tbody>
</table>

RESULTS AND DISCUSSION

The estimated AEE per minute for each posture (work stage) is provided in Table 5.

Table 5. AEE mean and STD. for each posture.

<table>
<thead>
<tr>
<th>Posture (work stage)</th>
<th>AEE mean (j/kg/min)</th>
<th>AEE STD.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1(S0T0)</td>
<td>56</td>
<td>34.3</td>
</tr>
<tr>
<td>2(S0T20)</td>
<td>68.32</td>
<td>35.2</td>
</tr>
<tr>
<td>3(S45T0)</td>
<td>68.24</td>
<td>27.97</td>
</tr>
<tr>
<td>4(S45T20)</td>
<td>81.18</td>
<td>38.24</td>
</tr>
<tr>
<td>5(S90T0)</td>
<td>82.06</td>
<td>31.41</td>
</tr>
<tr>
<td>6(S90T20)</td>
<td>94.85</td>
<td>44.2</td>
</tr>
</tbody>
</table>

Note: AEE=Activity Energy Expenditure; STD=Standard deviation

As can be seen from the table above, AEE increased with the increase of shoulder and trunk flexion. Working in posture 1 (neutral; S0T0) consumed the least amount of AEE (56 j/kg/min), whereas the posture 6 (S90T20) consumed the largest amount (94.85 j/kg/min). Working in posture 2 (S0T20) and posture 3 (S45T0) consumed approximately the same amount of AEE as well as postures 4 (S45T20) and 5 (S90T0). The summary statistics for the within-subject effects ANOVA on AEE is shown in Table 6. Shoulder and trunk flexion had a highly significant effect on AEE (P < 0.05).
The initial objective of the research was to identify the effect of shoulder and trunk flexion on AEE. The results of this study indicate that shoulder and trunk flexion have a significant effect on AEE. AEE increases with the increment of shoulder and trunk flexion away from the neutral posture (posture 1). This finding suggests that stress can be indicated by the amount of AEE. Although the association of shoulder and trunk flexion with AEE was not explored in literature, these results seem to be consistent with those of other research which found that working in non-neutral posture is stressful. Regarding the shoulder, this study agrees with Sasikumar and Lenin [10] who found that the stress is highest when the shoulder flexion is at the chest level, which is also consistent with those of Lee [9] who found that posture of shoulder/elbow 0°/90° has the highest personal holding ability. Conversely, these results disagreed with Brookham et al. [11] who found that 60° shoulder flexion and -45° internal rotation is an excellent posture. In trunk posture, these results are in agreement with the findings of Chung et al. [4], Saha et al. [5] and Damecour et al. [6] which showed that trunk flexion has a significant impact on physiological demands and subjective perception. Also, this finding is consistent with the result of De et al. [39], who concluded that a neutral trunk posture is the optimum standing posture. In contrast, this outcome is not consistent to that of Brookham et al. [11] and Kong et al. [3], who found that bending back forward at 45° with shoulder flexion at 45° lead to the least comfortable posture.

The second objective was to develop a model to estimate WE in horizontal drilling task. According to the data obtained, we can infer that the predicted mean of AEE after one hour of work can be estimated as in Equation 2.

\[
AEE_{h_i} = AEE_{i} \times 60 \text{ (j/kg/hour)}
\]  

(2)

Where

\(AEE_{h_i}\) the consumed energy during work of one hour/kg at posture i;

\(AEE_{i}\) the consumed energy during work of one minute/kg at posture i.

Working in neutral posture consumes the least amount of energy per hour among the other studied postures. This finding is consistent with those of other studies which reported that neutral posture is an optimum posture. Therefore, the energy consumed during working in neutral posture is the least energy and thus will be used in the suggested model as a reference for the estimation of the AWE due to unproductive movements during work versus all other postures as in equation 3. Thus, AWE is the difference between the energy consumed in each posture with the consumed energy while working in a neutral posture.

\[
AWE_{i} = AEE_{h,i} - AEE_{h,n}
\]  

(3)

Where

<table>
<thead>
<tr>
<th>Source</th>
<th>df</th>
<th>df (Error)</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shoulder</td>
<td>2</td>
<td>18</td>
<td>8.11</td>
<td>0.003</td>
</tr>
<tr>
<td>Trunk</td>
<td>1</td>
<td>9</td>
<td>9.93</td>
<td>0.012</td>
</tr>
<tr>
<td>shoulder * trunk</td>
<td>2</td>
<td>18</td>
<td>1.368</td>
<td>0.28</td>
</tr>
</tbody>
</table>

Table 6. The summary statistics for within-subject effects ANOVA of AEE.
AEEhₙ

the consumed energy for one hour during work in a neutral posture.

The general equation to estimate WE is in Equation 4.

\[
WE = \frac{\text{work done}}{\text{Energy expenditure}} \times 100 \, (\%)
\]  (4)

WE can be estimated by subtracting the AWE from AEE (To get the consumed productive energy) over AEE. Therefore, WE is calculated as in Equation 5.

\[
WE = \frac{AEEh₁ - AWE_i}{AEEh₁} = \frac{AEEhₙ}{AEEh₁} \, (\%)
\]  (5)

The estimated AWE and WE are shown in Figure 3 and Figure 4 respectively after working for one hour using the six coordinated postures of shoulder and trunk flexion.

*Figure 3. Activity waste energy (AWE) during work at shoulder and trunk flexion.*
CONCLUSION

A new approach to assessing the efficiency of work in manual handling tools was successfully developed. The assessment is based on the effects of shoulder and trunk flexion postures on AEE. Our results show that the consumed energy increase with the increment of the trunk and shoulder flexion away from the neutral posture in a highly statistically significant manner. Working in neutral posture consumes the lowest energy and thus considered optimally efficient. The shoulder at the chest level with moderate bending of the trunk (20°) consumes the highest energy and thus the least efficient. The coordinated postures between trunk and shoulder had different efficiencies. The major limitation of this study is the enormous number of possible coordinated postures to be studied. Additionally, More research should be undertaken for the investigation of the energy consumed by and the work efficiencies of different coordinated postures for upper and lower limbs, and how consuming more energy will affect efficiency and the health of the worker in the long term.
Work Efficiency Model Based on Posture in Horizontal Drilling Task

References


نموذج كفاءة العمل على أساس الموقف في مهمة الحفر الأفقي
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ملخص البحث
قد يساهم الوقوف غير المريح في العمل ليس فقط في تطور الاضطرابات العضلية الهيكليّة (MSDs) ولكن أيضًا كفاءة العمل (AEE) على أساس إنفاق طاقة النشاط (WE). لم يُحظِ قياس WE على أساس إنفاق طاقة النشاط (WE) بائتمام في أماكن العمل. الهدف من هذه الدراسة هو تطوير نموذج للوقوف في ماهية الحفر الأفقي. شارك في التجربة عشرة أفراد، جميعهم من الرجال بمسار عمر 23.3 ± 0.67. تم اختبار ستة أوضاع للفقرات بين الكتف والذراع. كانت WE و AEE في الدمغة المتكررة في ظل الوقوف بينما adapted the client's content as necessary. ANOVA 

الكلمات المفتاحية: إنفاق طاقة النشاط (AEE)، الطاقة المهدية للنشاط (AWE)، وضع (posture).