Musculoskeletal Load Assessment of the Upper Limb Positions Subjectively Chosen as the Most Convenient

Danuta Roman-Liu
Adam Wittek
Central Institute for Labour Protection, Poland

Krzysztof Kędzior
Warsaw University of Technology, Poland

Work posture is determined by interdependence between work stand design, the necessity to perform given activities, and the anthropometric dimensions of the worker, but it also depends on individual preferences. The aim of the study was to compare the musculoskeletal load of the right upper extremity under conditions of imposed (standard) upper limb position and subjectively chosen ones, and to assess the influence of the changes in magnitude of the external force on the musculoskeletal load in the examined limb positions. Ten healthy male participants took part in the study. Muscular load associated with different upper extremity positions with and without external load were assessed. Musculoskeletal load for standard and subjectively chosen limb positions and two different values of external load were compared by means of theoretical and experimental methods. Results indicate that differences in musculoskeletal load between imposed and subjectively chosen limb positions were not high enough to show statistically significant differences, and the upper limb position chosen by the participant does not always cause the lowest musculoskeletal load.

1. INTRODUCTION

Muscle effort of the upper extremity still plays an important role in contemporary working life causing risk of musculoskeletal disorders. The risk of musculoskeletal disorders is present in modern industry as well as in office work (Bjelle, Hagberg, & Michaelsson, 1979; Hunting, Grandjean, & Maeda, 1980). Muscle effort is enhanced by an improper work posture, by too big mass of moved objects and tools, and also by an improper frequency of repetitions. Research is conducted to find solutions that will help to lower musculoskeletal load and, consequently, to reduce the problem of musculoskeletal disorders. Results of studies (Kilbom & Persson, 1987; Melin, 1987) show that even work that does not seem very strenuous and shows very low or negligible energy expenditure can cause overload due to improper work technique.

Generally, there are three biomechanical factors influencing the workers' musculoskeletal load and health: body and limb posture, the magnitude and direction of the extension of the external forces, and the frequency of movement repetition. All those factors should be optimal...
when considered in relation to one another. The most convenient posture may be different for different values of external load and for different patterns of work. Work posture is determined by the interdependence between work stand design, the necessity to perform a given activity, and the anthropometric dimensions of the worker. In most cases, work posture is imposed by the factors just mentioned, but it also depends on individual preferences. It should be expected that posture chosen by the worker causes less musculoskeletal load than posture imposed by working conditions.

The problem of posture is becoming increasingly important, especially now that participatory ergonomics plays an increasingly important role. Therefore, it is important to study, by objective methods, the problem of musculoskeletal load for limb location preferred by a person in relation to musculoskeletal load in the imposed positions. Other factors, like the frequency of movements and the influence of the external load value on muscle load pattern, should also be considered. In this study, however, only the influence of limb position and external force on the musculoskeletal load, for a given frequency of repetition, were examined. The aim of the study was to

1. compare the musculoskeletal load of the right upper extremity in cases of imposed (standard) upper limb positions and subjectively chosen ones,
2. assess the influence of the changes in the magnitude of the external load on the musculoskeletal load in the examined limb positions.

Ten participants took part in the study, in which muscular load associated with different upper extremity positions and different values and directions of external load were assessed. Musculoskeletal load for standard and subjectively chosen limb positions and two different external loads were compared by means of theoretical and experimental studies.

### 2. PARTICIPANTS

Theoretical and experimental studies were performed on 10 young, healthy men (Table 1); the average age was 22.5 years, the average body mass was 73.7 kg, and the average body height was 179.7 cm. For the purpose of theoretical calculations, the length of an arm, forearm, and hand were measured. The mass of those parts was assessed with the Zaciorsky formula (Zaciorsky, Aruin, & Sieluyanov, 1981) on the basis of the whole body mass measurements.

<table>
<thead>
<tr>
<th>Initials</th>
<th>Body Mass (kg)</th>
<th>Body Height (cm)</th>
<th>Arm Length (cm)</th>
<th>Arm Mass (kg)</th>
<th>Forearm Length (cm)</th>
<th>Forearm Mass (kg)</th>
<th>Hand Length (cm)</th>
<th>Hand Mass (kg)</th>
<th>Age Years</th>
</tr>
</thead>
<tbody>
<tr>
<td>AA</td>
<td>72</td>
<td>171</td>
<td>24</td>
<td>1.96</td>
<td>23</td>
<td>1.16</td>
<td>20</td>
<td>0.44</td>
<td>20</td>
</tr>
<tr>
<td>AW</td>
<td>73</td>
<td>182</td>
<td>26</td>
<td>1.96</td>
<td>30</td>
<td>1.17</td>
<td>20</td>
<td>0.46</td>
<td>26</td>
</tr>
<tr>
<td>DC</td>
<td>85</td>
<td>187</td>
<td>28</td>
<td>2.30</td>
<td>27</td>
<td>1.33</td>
<td>22</td>
<td>0.52</td>
<td>25</td>
</tr>
<tr>
<td>DS</td>
<td>85</td>
<td>186</td>
<td>30</td>
<td>2.31</td>
<td>28</td>
<td>1.33</td>
<td>20</td>
<td>0.51</td>
<td>23</td>
</tr>
<tr>
<td>PR</td>
<td>63</td>
<td>172</td>
<td>26</td>
<td>1.68</td>
<td>27</td>
<td>1.03</td>
<td>20</td>
<td>0.41</td>
<td>18</td>
</tr>
<tr>
<td>PW</td>
<td>70</td>
<td>172</td>
<td>26</td>
<td>1.89</td>
<td>26</td>
<td>1.13</td>
<td>21</td>
<td>0.44</td>
<td>20</td>
</tr>
<tr>
<td>SR</td>
<td>69</td>
<td>183</td>
<td>28</td>
<td>1.83</td>
<td>27</td>
<td>1.11</td>
<td>20</td>
<td>0.45</td>
<td>25</td>
</tr>
<tr>
<td>SZ</td>
<td>64</td>
<td>176</td>
<td>28</td>
<td>1.70</td>
<td>26</td>
<td>1.04</td>
<td>21</td>
<td>0.42</td>
<td>24</td>
</tr>
<tr>
<td>WS</td>
<td>73</td>
<td>176</td>
<td>27</td>
<td>1.97</td>
<td>24</td>
<td>1.17</td>
<td>20</td>
<td>0.45</td>
<td>24</td>
</tr>
<tr>
<td>TB</td>
<td>83</td>
<td>192</td>
<td>30</td>
<td>2.23</td>
<td>28</td>
<td>1.30</td>
<td>23</td>
<td>0.52</td>
<td>20</td>
</tr>
</tbody>
</table>
3. METHODS

3.1. Experimental Method

The experimental method consisted of surface electromyography (EMG) signal registration and analysis. Eight big muscles of the upper extremity located just under the skin, thus relatively easy to examine by surface EMG, were chosen for examination: biceps brachii caput breve (BBCB), brachioradialis (BR), triceps brachii caput laterale (TBCL), deltoideus (DL), flexor carpi radialis (FCR), flexor carpi ulnaris (FCU), extensor carpi ulnaris (ECU), and muscle trapezius (TRP). The muscles chosen for examination were considered representative of the upper limb with the assumption that the muscle load in those muscles reflects the muscle load of the upper extremity. The additionally chosen muscle trapezius plays a major role in supporting scapula and is taken by many researchers as a muscle that can serve as an indicator of the whole limb load (Christensen, 1986; Lannersten & Harms-Ringdahl, 1990).

Musculoskeletal load was assessed by means of an EMG signal registered by surface electrodes with a frequency of 2 times per minute during an isometric contraction of muscles. Electrodes were placed along muscle fibers at a 2-cm distance from each other. Before attaching the electrodes, the skin was cleaned, and the epidermis was removed. Conductive gel was used to decrease the skin–electrode resistance below 2 kΩ. Two apparatus for measuring the EMG signal were used: a four-channel physiometer PHY-400 produced by Premed (Norway), by which arm muscles BBCB, DL, TBCL, and TR were measured, and a four-channel Beckman R 411 for measuring signals from the ECU, FCU, BR, and FCR muscles. Analog signals from both of those apparatus were digitized with the frequency of 2 kHz through a 12-bit analog/digital transducer and sent to a PC/AT (66 MHz, 16 MB) IBM compatible computer.

In the experimental method, two parameters were chosen as indicators of the muscular load in a given limb position: amplitude of EMG signal (AMP) and slope of zero crossing (SZC). Amplitude of EMG is commonly considered as an indicator of muscular force (Lawrence & DeLuca, 1983). It was calculated as root mean square from the first EMG signal measurement. The amplitude value was normalized to the maximum amplitude value, which was measured before each experiment as the amplitude for maximal voluntary contraction force. The parameter that showed changes in muscles in the course of the experiment and was interpreted as an indicator of muscular fatigue was zero crossing. Parameter SZC was calculated as the value of the slope of the regression line between time (independent variable) and zero crossing (dependent variable; Hägg, 1981; Hägg, & Suurküla, 1991; Inbar, Allin, Paiss, & Kranz, 1986).

3.2. Theoretical Method

The theoretical method was based on a computer model of the upper extremity, which consists of an open kinematics chain of 7 degrees of freedom composed of three rigid links (arm, forearm, and hand; Kędzior, Roman, & Rzymkowski, 1993a, 1993b, 1993c). It is assumed that the trunk is immobile and the global system is joined to it. Joints have been modeled as rotating kinematics pairs of third class (the shoulder joint) and fourth class (the elbow joint and the wrist joint). Also, 34 upper extremity muscles are modeled. The mathematical model of the limb was generated by using the Denavit-Hartenberg local coordinate system (Denavit & Hartenberg, 1955). The geometrical and inertial data of the model were adopted on the basis of Siereg and Arvicar (1989).

The model accounts for all substantial movements of the upper limb abduction/adduction and rotation in the axis of the long bone in the arm joint; flexion/extension in the elbow joint and pronation/supination in the elbow-wrist joint; flexion/extension and abduction/adduction in the wrist joint. Input data for the muscle forces calculations are the length and mass of the three links (arm, forearm, and hand), upper extremity location defined by seven parameters (angles between links), and external force vector (value and direction). Theoretical calculations were performed for each participant separately, on the basis of upper extremity links
length measurements and links mass calculations (Table 1). The parameter that expressed muscle forces calculated from the model was named MOD. For each participant, MOD parameters for eight muscles (the same as in the experimental studies) were analyzed. As muscle trapezius was not taken into account in the model, parameter MOD for this muscle was expressed as the sum of the forces in all 34 muscles.

3.3. The Experimental Setup
Experiments were performed for six different upper extremity locations in two different work areas (Figure 1). Three of them were in the standing position (I1, I2, I3) and three were in the sitting position (I4, I5, I6). The limb position was defined in terms of the angles between the trunk and the arm, the arm and the forearm, and the forearm and hand in the flexion/extension and abduction/adduction planes. Engagement of the upper extremity muscles was examined when the limb was loaded only with its own load and also when it was loaded with additional external load. So, for each limb location, experiments with and without external load were performed, which resulted in 12 variants of experiments. Variants with external load were marked L, and variants without external load were marked U (Figure 1).

In variants with external load in the sitting position, the force was exerted vertically. In the standing position, it was exerted horizontally. In both work areas, two of the limb positions were standard, the same for every participant, and one of them was subjectively chosen by every participant as the most convenient one. For standard limb positions, those limb locations that were comparably easy to measure and define were chosen. For the standing position, the standard limb positions were I1 and I2 (Figure 2), and the subjectively chosen one was I3. For the sitting position, the standard limb positions were I4 and I5, and the subjectively chosen was called I6.

![Figure 1. Names of variants for different limb load and location.](image-url)
In variants without external load, the task was to keep the upper extremity in a given position. In variants with external load, the participants kept their upper extremity in a given position and pushed the push button with a force of 20 N and a frequency 4 times per minute (10 s of pushing with a 5-s rest). The participants observed on a monitor the line of the real force they exerted on the push button and the line of the force with which they should have pushed the button. In this way, the participants had feedback from the force value. The task was to keep those two lines together. Participants were also told to keep their head straight, without movement. Experiments lasted for maximum 15 min. If participants felt very tired, they were allowed to finish the experiment earlier. One experimental session consisted of two experiments: without external load and with external load for the same limb location. There was a 30-min break between the experiments, which allowed for the recovery of muscles (Funderburgh, Hippskind, Welton, & Lind, 1974).

3.4. Analysis
The purpose of the analysis was to find differences in experimental (AMP and SZC) and theoretical (MOD) parameters between subjective and standard variants of limb locations, and to find differences in the values of those parameters for each muscle between variants with and without external load. Variance analysis was performed to differentiate values of the analyzed parameters (MOD, AMP, SZC) between the subjectively chosen positions of the limb and the positions that were obligatory for all participants, and between the variants with and without external load. Statistical analysis was done by means of nonparametric variance analysis (Wilcoxon rank test). The typical ANOVA procedure was not appropriate because it demands normal distribution. In variance analysis, particular positions of the upper extremity, muscle, and participant's name were interpreted as factors. Zero hypothesis was rejected when $p < .05$.

Figure 2. Standard upper limb locations in variants 11, 12, 14, 15.
In order to perform complex differentiation of the limb location for each of the three analyzed parameters, the parameter Ratio of Location was calculated. It is the quotient of the average values of parameters for two analyzed limb positions. This allowed for the quantification of the differences in load between the variants of experiments (standard and subjectively chosen limb locations). The calculations and the analysis of results were performed separately for variants with and without external load. Analysis was performed between variants from the same work area (force exerted vertically or horizontally) and between variants that belonged to two different areas. For each experimental variant, there were three values of the Ratio of Location: one for each of the three analyzed parameters (AMP, MOD, SZC). For each parameter, the average value was calculated from 80 values (8 muscles for 10 participants). The Ratio of Location values belonged to one of the two ranges. The value was lower than 1, or the value was higher than 1. The Ratio of Location for all of the three analyzed parameters did not always belong to the same range. In cases where none of the Ratios of Location were statistically significant, tendencies showed by two of them qualified the variant. In cases where at least one of the differences was statistically significant, the statistically significant parameter was taken as an indicator for the whole group.

To analyze the differences in the MOD, AMP, and SZC parameters between variants with and without external load for each of the examined muscles, the parameter Ratio of Load was calculated. This is the quotient of the average values of the analyzed parameters for variants with and without external load. The average value for each parameter was calculated from 60 values (6 variants for 10 participants). Similar to the Ratio of Location, the values of the Ratio of Load for each of parameters (MOD, AMP, and SZC) and for each examined muscle belonged to one of the two ranges. It was either higher or lower than 1 and the analysis was performed in the same way as for limb location.
4. RESULTS

4.1. Analysis of Limb Location

Figure 3 presents the values of the Ratio of Location for compared standard and subjectively chosen variants of limb locations without external load. There were no statistically significant differences between subjectively chosen and standard limb locations in variants without external load. In seven cases, all the three Ratios of Location belonged to the same range. In two cases, the Ratios of Location for AMP and MOD were in the same range, that is, higher than 1, and for SZC, it was lower than 1.

Figure 4 presents values of the Ratio of Location for variants with external load. In six cases, the differences between two different limb locations were statistically significant. In five cases, the Ratios of Location for all three parameters were in the same range. In three cases, the Ratio of Location for SZC was in a different range than for AMP and MOD. In one case, the Ratio of Location (for the AMP parameter) was in a different range than the another two, but only the differences for AMP were statistically significant. That is why, in the next step of analysis, the differences for 14/13 were taken as belonging to the range higher than 1.

4.2. Analysis of Load

Values of the Ratio of Load for all three parameters and all examined muscles are presented on Figure 5. Statistically significant differences occurred in 20 out of 24 cases. For parameter AMP, the differences were statistically significant for all cases. For four muscles (DL, FCU, FCR, and TR), the differences were statistically significant for all parameters. In four cases, there were no statistically significant differences for fatigue parameter SZC. For muscle BBCB, the Ratio of Load for parameter MOD was lower than 1, whereas the Ratios of Load for EMG parameters were higher than 1. A similar situation occurred for the ECU muscle. For two muscles, FCU and FCR, for variants without external load, the average
Figure 4. Values of the Ratio of Location between standard and subjectively chosen limb positions for variants with external load for all examined muscles.

Figure 5. Values of the Ratio of Load for eight examined muscles.
value of the MOD parameter was 0, so it was not possible to calculate the Ratio of Load for MOD for those muscles.

5. DISCUSSION

The variants of limb locations marked I1, I2 (standard limb locations), and I3 (subjectively chosen limb location) were examined in the work area for force exerted horizontally. Variants marked I4, I5 (standard limb locations), and I6 (subjectively chosen limb location) were examined in the work area for force exerted vertically. In the first work area (force exerted horizontally) in both cases, that is, variants without and with external load, the muscular load in I3 was lower than in I1 but higher than in I2. In all those cases, the differences were not statistically significant. In the second work area (force exerted vertically), the muscular load for limb location I6 was higher than for I5 in both cases, that is, without and with additional external load. In variants without external load, I6 was also lower than I4 with differences statistically not significant. However, in variants with external load, the muscular load for I6 was higher than for I4. It shows that musculoskeletal load for subjectively chosen variants of limb location was not significantly higher or lower than in variants with imposed limb location. Standard limb locations—variants I2 and I5—were supposed to cause very low musculoskeletal load, whereas in the variants I1 and I4, musculoskeletal load was supposed to be high. Musculoskeletal load in subjectively chosen limb positions was somewhere between very strenuous and hardly strenuous positions, without statistically significant differences, however.

A general analysis comparing variants of limb location in both examined work areas together showed that for variants without external load, there were no statistically significant differences between the examined variants, which means that musculoskeletal load was similar in subjectively chosen and standard positions. The subjectively chosen limb position marked I6 was more strenuous than the subjectively chosen I3. Also, the muscular load in the I6 variant was higher than in the variants for standard limb positions I2 and I5. The subjectively chosen variant I3 caused higher muscular load than variant I2 but lower than variant I4. There were the same tendencies in variants with and without external load in six out of nine cases. In most of the cases, the differences were not statistically significant and the values of the Ratio of Location were very close to 1. This means that tendencies rather than differences should be discussed and suggests that subjectively chosen upper limb positions did not cause much lower musculoskeletal load than standard limb positions.

Thus, the question arises why those specific positions were chosen by participants as the most convenient ones. When choosing a convenient limb location, the participants were not restricted in time. They could try which limb location felt more comfortable. They were also allowed to push the push button in order to check the required force. When choosing a limb position, the participants probably did not pay much attention to the fact that they would also exert an additional external load. However, also in variants without external load, the subjectively chosen limb positions do not seem much less strenuous than standard limb positions. This suggests that the differences in muscular load were too small. Additional external load caused statistically significant differences in some cases. What is more, this also changed the tendencies of muscular load differentiation. There are bigger differences between standard and subjective limb positions for variants with external load than for those without. In variants with external load, the muscular load was generally higher so the differences were easier to be detected. It should also be mentioned that statistically significant differences in variants with external load occurred between variants of limb locations from two different work areas, which supports the thesis that differences in musculoskeletal load within one work area were too small.

In three cases, the additional external load caused changes in the musculoskeletal load pattern. In variants with external load, the limb location marked I6 caused higher muscular load than I1 and I4, but in variants without external load, the muscular load in I6 was lower than in I1 and I4. In the third case, in variants without external load, the limb location marked I3 was more strenuous than I5, but in variants with external load, I3 was less strenuous. The
subjectively chosen posture was the same for variants with and without external load, which means that external load caused some changes in the musculoskeletal load in the examined muscles for the examined variants of limb positions. This is confirmed by the Ratio of Load, which showed that in all muscles, the muscular load in variants with external load was higher than in those without, but the increase of load was not the same in all muscles. It was much higher for FCU, FCR, and TBCL than for BBCB or BR, which means that the external load does not increase every muscle load to the same degree. So, there is an influence of external load on the musculoskeletal load, and it is not proportional. Additional external load causes different patterns of distribution of load among the examined muscles.

Too small differences (not statistically significant) between the experimental variants may have been caused by a big influence of the external load—higher than that of limb location. The results of both experimental and theoretical studies suggest that there are higher differences in muscular load due to external load value than due to limb location, which is in step with Habes's results (Habes, Carlson, & Bader, 1985), who showed that external load value differentiates muscle fatigue to a higher degree than limb location. It cannot be concluded that muscle load in subjectively chosen limb positions was significantly higher than in standard positions. Moreover, it was not lower, which should have been expected.

6. CONCLUSIONS

Results indicate that in a restricted work area the differences in musculoskeletal load between imposed and subjectively chosen limb positions are not big enough to show statistically significant differences, and the upper limb positions chosen by the participants do not always result in the lowest musculoskeletal load. Relatively high and not proportional changes of musculoskeletal load due to external load value confirmed that, in the design process, factors connected with posture and external load should be considered together, not separately.

REFERENCES


