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TORQUE OF THE OPERATOR'S UPPER EXTREMITY IN RELATION TO ITS ORIENTATION WITHIN A NORMAL WORKING SPACE

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K e y w o r d s: torque of the upper extremity, ergonomy, anthropometry.

A b s t r a c t

This paper presents the results of a study into the effect of some factors determining the orientation of the upper extremity within the normal working space on the torque of the muscles of this extremity. The results of this study may be useful in the anthropotechnical design of controlling devices. The paper also includes data on the torque developed by the upper extremity within the operator's normal working space which are presented in the form of centile characteristics.

MOMENT SKRĘCAJĄCY KOŃCZYNY GÓRNEJ OPERATORA W ZALEŻNOŚCI OD JEJ POŁOŻENIA W NORMALNEJ PRZESTRZENI PRACY

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S ł o w a k l u c z o w e: moment skręcający kończyny górnej, ergonomia, antropometria.

A b s t r a k t

W pracy przedstawiono wyniki badań dotyczących wpływu wybranych czynników określających położenie kończyny górnej w normalnej przestrzeni pracy na wartość momentu skręcającego rozwijanego przez mięśnie tej kończyny. Wyniki badań mogą być wykorzystane w antropometrycznym projektowaniu urządzeń sterujących. Przedstawiono także, w formie charakterystyk centylowych, dane dotyczące momentów skręcających rozwijanych przez kończynę górną w normalnej przestrzeni pracy operatora.

Introduction

Performing work by humans with the use of machines is made possible through controlling elements which correspond to human motory output and elements which carry information in the form of mental stimuli, corresponding to human sensory input. Machines can be controlled through various elements such as levers, pedals, steering wheels, manual wheels, rotating hand grips and knobs. The task of a designer is to select the most appropriate element in the best form for a given control, also in terms of shape and size (SŁOWIKOWSKI 2000).

Another important element is the choice of force applied by a human – operator to the controlling element.

The objective of the study was to describe the effect of some factors determining the orientation of the upper extremity within the normal working space on the torque of the muscles of this extremity.

The effect of the following factors on the mean values of the maximum torque of the upper extremity were studied: the extremity (right, left), the value of the angle determining the orientation of the extremity and the measurement plane in which the pronation and supination movements were conducted.

The results of the study are new data within the scope of the operator's biomechanical competences. The results of this study may be useful in the anthropotechnical design of controlling devices.

Method

Subject of the study

The study involved 300 persons (124 women and 176 men) aged 21-48. The majority of the subjects were young and working or students. Based on an interview it was found that they were healthy. The study excluded left-handed persons due to possible functional asymmetry of the upper extremities.

Table 1 presents a complete description of the subject of the study.

Sample size

The sample size was established according to the representation method by unlimited dependant draw (draw with no return) (GREŃ 1984, POLAŃSKI, PIETRASZEK 2001). The initial sample size was: For women $n_1 = 124$, for men $n_2 = 176$.

Table 1

Anthropometric characteristics of the studied women and men

Specification of characteristics	Statistical parameters									
	women					men				
	mean value*	standard deviation*	variation coefficient [%]	median (C_{50})*	range*	mean value*	standard deviation*	variation coefficient [%]	median (C_{50})*	range*
Age [years]	26.68	6.2471	23.42	24.0	19.0	27.14	6.2936	23.19	25.0	26.0
Height [cm]	163.53	5.3711	3.28	163.0	20.0	175.90	17.6894	10.06	177.3	126.0
Body weight [kg]	59.84	10.7927	18.04	56.7	40.2	81.72	15.0975	18.48	80.0	90.0
Right arm length [cm]	16.47	0.8434	5.12	16.3	2.9	17.97	0.8071	4.49	18.0	3.3
Left arm length [cm]	16.25	0.8918	5.49	16.1	3.6	17.89	0.8430	4.71	17.9	3.4
Right hand length [cm]	8.29	0.5428	6.54	8.3	2.2	8.88	0.6262	7.05	9.0	3.1
Left hand length [cm]	8.12	0.5067	6.24	8.1	2.2	8.87	0.5464	6.16	8.9	2.6
Right arm width [cm]	7.84	0.4038	5.15	7.8	1.5	9.00	0.4810	5.34	9.1	2.1
Left arm width [cm]	7.66	0.4013	5.24	7.7	1.5	8.82	0.4397	4.98	8.8	1.9
Right carpal bone width [cm]	5.48	0.3870	7.07	5.4	1.4	6.33	0.3905	6.17	6.3	2.1
Left carpal bone width [cm]	5.36	0.3684	6.87	5.3	1.3	6.16	0.4442	7.21	6.1	2.2
Right hand joint circumference [cm]	15.50	0.9372	6.05	15.4	4.5	17.75	0.8849	4.98	17.7	4.6
Left hand joint circumference [cm]	15.36	0.7088	4.61	15.3	3.2	17.61	0.8573	4.87	17.5	4.6
Right hand fingers thickness [cm]	3.08	0.3247	10.53	3.1	1.5	3.56	0.2896	8.14	3.6	1.4
Left hand fingers thickness [cm]	3.03	0.2809	9.26	3.1	1.2	3.52	0.2315	6.58	3.5	1.1

* – values in units of a given characteristic

For the sample sizes in the particular groups of the study that were greater than the requisitive (for women n_o = 123, for men n_o = 78), they were acknowledged sufficient.

Measuring devices

The torque was measured with the use of a specially constructed prototype measuring device.

Figure 1 presents a simplified operation principle of the measuring device.

The mechanical system through the spring mechanism produces a lineary incrementing torque in the function of the rotation angle. The electronic module measures the rotation angle, the torque and displays the results on the display.

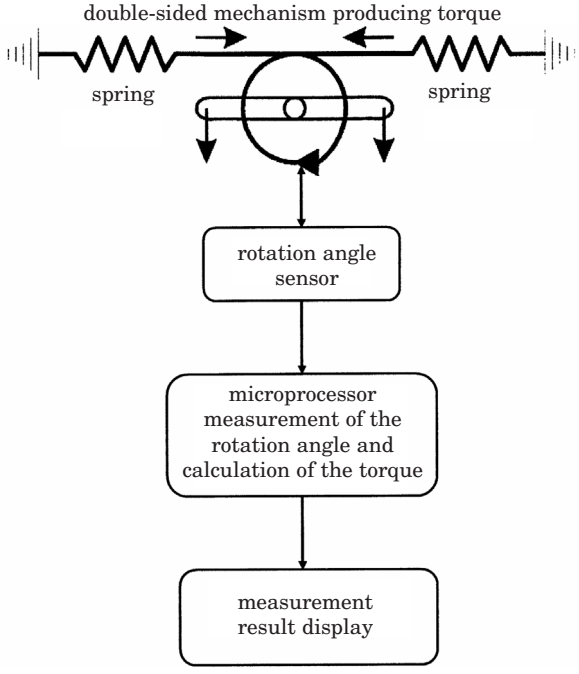

Fig. 1. Flow chart of the measuring stan

Source: own elaboration.

Scope of the study

The initial position was determined as the intersecting point of the horizontal and the vertical planes with the axis of the ulnar articulation which is the centre of the motion space. The subjects were in the imposed sitting position.

The measurements in the vertical plane were carried out at the angle $\alpha = \{+30^o; 0^o; -30^o\}$ (upwards „+" ; downwards „–") (Fig. 2b)), whereas the measurements in the horizontal plane at the angle $\alpha = \{+30^o; 0^o; -30^o\}$ (inwards „-" ; outwards „+") (Fig. 2a).

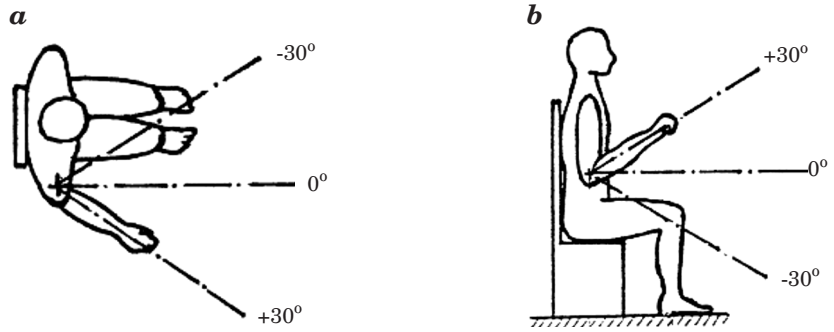

Fig. 2. Location of the upper extremity during the measurements of the torque: *a* – in the horizontal plane; *b* – in the vertical plane

Source: own elaboration.

In each of the five orientations, the subjects performed the pronation and supination movement of a continuous turn at the maximum strength which was recorded.

Statistical analysis

The experimental results were analysed with the use of the StatisticaPL and the WINSTAT software packages.

The following statistical procedures were applied:

– Basic statistical measures to determine the location and dispersion;
– Variance analysis;

The following basic measures of location and dispersion of the torque values for women and men were determined: Mean value, standard deviation, variance co-efficient, median (centile C_{50}), modal value, minimum value, maximum value, range, centile C_5, centile C_{95} (HAŁACZ 2008).

The variance analysis was carried out by evaluating the independent effect of the following factors: the extremity (right, left), the value of the angle determining the orientation of the extremity and the measurement plane in which the pronation and supination movements were conducted on mean values of the studied torque, separately for women and men. Moreover, the interactions of these factors were taken into account.

The following hypotheses were verified:

The zero hypothesis (H_o): the assumed experimental factors (the extremity, the value of the angle determining the orientation of the extremity and the measurement plane) do not have a significant effect on the mean values of the torque for women (men) at pronation (supination).

The alternative hypothesis (H_1): the mean values of torque for women (men) at pronation (supination) differ depending on the extremity, the value of the angle determining the orientation of the extremity and the measurement plane.

Results

The variance analysis results were presented below. Due to the large amount of data, the analysis does not cover the results reflecting the interactions between the studied factors, nevertheless such analysis was performed.

Tables 2–5 presents the results of the statistical comparison of the torque in relation to the assumed factors separately for women and men and movement direction (pronation – supination).

The following marking system was assumed in this study:

Factor *A* – extremity (R – right, L – left)

Factor *B* – value of the angle determining the measuring position ($a - \alpha = -30^o$; $b - \alpha = 0^o$; $c - \alpha = +30^o$)

Factor *C* – measurement plane (I – horizontal plane, II – vertical plane).

Based on the results it was found that statistically significant differences in the torque values for women at pronation occurred only for the different extremities. The mean value of torque for the right extremity (6.06 Nm) was greater than for the left extremity (5.70 Nm). As far as the other factors are concerned, i.e. group *B* and group *C* factors, statistically significant differences in the mean values of torque do not occur.

For supination, statistically significant differences in the torque values occur in relation to the kind of plane of measurement. The mean value of torque for the horizontal plane (5.97 Nm) was greater than for the vertical plane (5.74 Nm).

For the other factors, i.e. the group *A* and *B* factors, statistically significant differences were not found.

Table 2

Results of statistical comparison of the torque values at pronation depending on the assumed factors – women

Not including the *B* and *C* group factors			
Factor *A*	Mean value [Nm]	Standard deviation [Nm]	Variation coefficient [%]
R – right	6.06	0.9934	16.40
L – left	5.70	1.0868	19.06
Difference significance results (Duncan test): $P > L^{**}$			
Not including the *A* and *C* group factors			
Factor *B*	Mean value [Nm]	Standard deviation [Nm]	Variation coefficient [%]
$a - \alpha = -30^{o}$	5.84	1.1267	19.31
$b - \alpha = 0^{o}$	5.88	1.1025	18.74
$c - \alpha = +30^{o}$	5.92	0.9307	15.72
Difference significance results (Duncan test): No statistically significant differences			
Not including the *A* and *B* group factors			
Factor *C*	Mean value [Nm]	Standard deviation [Nm]	Variation coefficient [%]
I – horizontal plane	5.92	1.0312	17.42
I – vertical plane	5.84	1.0787	18.48
Difference significance results (Duncan test): No statistically significant differences			

Calculations were carried out at the significance level of $\alpha = 0.05$.

** – statistically significant differences at the significance level of $\alpha = 0.01$,

* – statistically significant differences at the significance level of $\alpha = 0.05$.

Table 3

Results of statistical comparison of the torque values at supination depending on the assumed factors – women

Not including the *B* and *C* group factors			
Factor *A*	Mean value [Nm]	Standard deviation [Nm]	Variation coefficient [%]
R – right	5.93	0.9963	16.81
L – left	5.78	1.0636	18.40
Difference significance results (Duncan test): No statistically significant differences			
Not including the *A* and *C* group factors			
Factor *B*	Mean value [Nm]	Standard deviation [Nm]	Variation coefficient [%]
$a - \alpha = -30^{o}$	5.86	0.9407	16.05
$b - \alpha = 0^{o}$	5.72	1.1162	19.52
$c - \alpha = +30^{o}$	5.98	1.0220	17.09
Difference significance results (Duncan test): No statistically significant differences			
Not including the *A* and *B* group factors			
Factor *C*	Mean value [Nm]	Standard deviation [Nm]	Variation coefficient [%]
I – horizontal plane	5.97	1.0392	17.42
I – vertical plane	5.74	1.0146	17.67
Difference significance results (Duncan test): I > II*			

Calculations were carried out at the significance level of $\alpha = 0.05$.

** – statistically significant differences at the significance level of $\alpha = 0.01$,

* – statistically significant differences at the significance level of $\alpha = 0.05$.

Table 4

Results of statistical comparison of the torque values at pronation depending on the assumed factors – men

Not including the *B* and *C* group factors			
Factor *A*	Mean value [Nm]	Standard deviation [Nm]	Variation coefficient [%]
R – right	8.29	0.8926	10.76
L – left	8.12	0.8590	10.57
Difference significance results (Duncan test): $P > L^{**}$			
Not including the *A* and *C* group factors			
Factor *B*	Mean value [Nm]	Standard deviation [Nm]	Variation coefficient [%]
$a - \alpha = -30^{o}$	8.41	0.9319	11.07
$b - \alpha = 0^{o}$	8.08	0.7915	9.79
$c - \alpha = +30^{o}$	8.13	0.8767	10.79
Difference significance results (Duncan test): $a > b, c^{**}$			
Not including the *A* and *B* group factors			
Factor *C*	Mean value [Nm]	Standard deviation [Nm]	Variation coefficient [%]
I – horizontal plane	8.14	0.8031	9.87
I – vertical plane	8.28	0.9456	11.42
Difference significance results (Duncan test): No statistically significant differences			

Calculations were carried out at the significance level of $\alpha = 0.05$.

** – statistically significant differences at the significance level of $\alpha = 0.01$,

* – statistically significant differences at the significance level of $\alpha = 0.05$.

Table 5
Results of statistical comparison of the torque values at supination depending on the assumed factors – men

Not including the *B* and *C* group factors			
Factor *A*	Mean value [Nm]	Standard deviation [Nm]	Variation coefficient [%]
R – right	8.23	0.8755	10.63
L – left	8.17	0.8537	10.45
Difference significance results (Duncan test): No statistically significant differences			
Not including the *A* and *C* group factors			
Factor *B*	Mean value [Nm]	Standard deviation [Nm]	Variation coefficient [%]
$a - \alpha = -30^{o}$	8.29	0.8278	9.98
$b - \alpha = 0^{o}$	8.10	0.9688	11.95
$c - \alpha = +30^{o}$	8.21	0.7802	9.50
Difference significance results (Duncan test) No statistically significant differences			
Not including the *A* and *B* group factors			
Factor *C*	Mean value [Nm]	Standard deviation [Nm]	Variation coefficient [%]
I – horizontal plane	8.33	0.8193	9.84
I – vertical plane	8.08	0.8909	11.03
Difference significance results (Duncan test): I > II*			

Calculations were carried out at the significance level of $\alpha = 0.05$.
** – statistically significant differences at the significance level of $\alpha = 0.01$,
* – statistically significant differences at the significance level of $\alpha = 0.05$.

Based on the results, it was found that statistically significant differences in the torque values for men at pronation occurred for the different extremities. The mean value of torque for the right extremity (8.29 Nm) was greater than for the left extremity (8.12 Nm). Significant differences were also recorded for the angle determining the measurement location. The mean value of torque for $\alpha = -30^{o}$ (8.41 Nm) was greater than for the other angles. No statistically significant differences were found for the group *C* factors (plane of measurement).

For supination, statistically significant differences in the torque values occur only in relation to the kind of plane of measurement. The mean value of torque for the horizontal plane (8.33 Nm) was considerably greater than for the vertical plane (8.08 Nm). For the other factors i.e. the group *A* and *B* factors statistically significant differences were not found.

In order to complement the above study results, tables 6 and 7 present torque mean values in the horizontal and vertical planes and the values of centiles C_5, C_{50} and C_{95} in the normal operator space. This data may serve as guidance for designers.

Table 6

Statistical parameters of torque in the horizontal plane

Specification	Women				Men			
	mean value [Nm]	centile C_5 [Nm]	median C_{50} [Nm]	centile C_{95} [Nm]	mean value [Nm]	centile C_5 [Nm]	median C_{50} [Nm]	centile C_{95} [Nm]
Torque of the right extremity at pronation in the orientation of $\alpha = -30^o$	6.16	5.0	5.9	7.9	8.25	6.9	8.3	9.5
Torque of the right extremity at supination in the orientation of $\alpha = -30^o$	6.26	4.4	6.1	8.5	8.44	7.1	8.4	10.2
Torque of the right extremity at pronation in the orientation of $\alpha = 0^o$	6.06	4.1	6.2	7.6	8.20	7.0	8.2	9.7
Torque of the right extremity at supination in the orientation of $\alpha = 0^o$	6.18	4.6	6.1	7.6	8.31	7.1	8.3	9.6
Torque of the right extremity at pronation in the orientation of $\alpha = 30^o$	6.16	5.0	6.1	7.6	8.18	6.8	8.2	9.7
Torque of the right extremity at supination in the orientation of $\alpha = 30^o$	5.93	4.8	5.9	7.1	8.27	7.3	8.3	9.5
Torque of the left extremity at pronation in the orientation of $\alpha = -30^o$	5.83	4.2	5.8	7.2	8.13	7.1	8.1	9.3
Torque of the left extremity at supination in the orientation of $\alpha = -30^o$	5.87	4.1	5.8	8.0	8.44	7.2	8.5	9.7
Torque of the left extremity at pronation in the orientation of $\alpha = 0^o$	5.70	3.8	5.7	7.6	7.97	6.9	7.9	9.3
Torque of the left extremity at supination in the orientation of $\alpha = 0^o$	5.78	4.2	5.6	7.8	8.11	7.0	8.0	9.4
Torque of the left extremity at pronation in the orientation of $\alpha = 30^o$	5.61	3.8	5.6	7.1	8.09	7.1	8.1	9.2
Torque of the left extremity at supination in the orientation of $\alpha = 30^o$	5.64	4.2	5.5	7.2	8.21	7.0	8.2	9.8

Source: HAŁACZ (2008).

Table 7

Statistical parameters of torque in the vertical plane

Specification	Women				Men			
	mean value [Nm]	centile C_5 [Nm]	median C_{50} [Nm]	centile C_{95} [Nm]	mean value [Nm]	centile C_5 [Nm]	median C_{50} [Nm]	centile C_{95} [Nm]
Torque of the right extremity at pronation in the orientation of $\alpha = -30^o$	5.76	4.2	5.4	8.3	8.67	7.3	8.5	10.5
Torque of the right extremity at supination in the orientation of $\alpha = -30^o$	5.53	4.0	5.4	6.9	7.75	6.3	7.7	9.4
Torque of the right extremity at pronation in the orientation of $\alpha = 0^o$	6.06	4.1	6.2	7.6	8.20	7.0	8.2	9.7
Torque of the right extremity at supination in the orientation of $\alpha = 0^o$	6.18	4.6	6.1	7.6	8.31	7.1	8.3	9.6
Torque of the right extremity at pronation in the orientation of $\alpha = 30^o$	6.12	5.1	6.0	7.3	8.27	6.7	8.4	9.8
Torque of the right extremity at supination in the orientation of $\alpha = 30^o$	6.11	4.9	6.0	7.7	8.28	7.1	8.3	9.4
Torque of the left extremity at pronation in the orientation of $\alpha = -30^o$	5.59	4.1	5.2	8.6	8.61	7.1	8.5	10.4
Torque of the left extremity at supination in the orientation of $\alpha = -30^o$	5.21	3.9	4.9	7.8	7.79	6.5	7.7	9.9
Torque of the left extremity at pronation in the orientation of $\alpha = 0^o$	5.70	3.8	5.7	7.6	7.97	6.9	7.9	9.3
Torque of the left extremity at supination in the orientation of $\alpha = 0^o$	5.78	4.2	5.6	7.8	8.11	7.0	8.0	9.4
Torque of the left extremity at pronation in the orientation of $\alpha = 30^o$	5.79	4.5	5.5	7.6	8.40	7.2	8.2	10.3
Torque of the left extremity at supination in the orientation of $\alpha = 30^o$	5.77	3.8	5.8	7.7	7.96	6.7	8.0	9.2

Source: HAŁACZ (2008).

Results

Based on the statistical analysis of the experimental results, the following conclusions can be drawn:

1. Based on the results of verification of the statistical hypotheses, the correlation between the torque and the extremity (left, right) was found only for pronation (inward motion). Both in women and men the mean torque values for the right extremity (women – 6.06 Nm, men – 8.29 Nm) were greater than for the left extremity (women – 5.70 Nm, men – 8.12 Nm). This is confirmed by a proven occurrence of functional asymmetry.

During supination (outward motion), the type of extremity did not have an effect on the torque mean values. However, based on the statistical analysis it

was found that during supination, another factor, i.e. the plane of motion, has an effect on the results. In both women and men the mean torque values obtained for the horizontal plane (women – 5.97 Nm, men – 8.33 Nm) are significantly greater than for the vertical plane (women – 5.74 Nm, men – 8.08 Nm). Such a correlation was not recorded for pronation.

According to the author, it is possible that the difference resulting from the functional asymmetry of the extremities was bridged by a more significant factor, i.e. the plane of motion. It is also significant that for both the women and the men the studied correlations are the same. It is probable that the vertical plane is more natural and convenient for conducting turning motions and for the supination, the plane type plays a more important role.

2. While verifying the statistical hypotheses it was also found that some interactions have a significant effect on the torque value.

In all the cases, except pronation in women, the combined effect of the following factors was recorded: plane of measutrement and angle determining the location of measurement. At supination in both women and men the best results were obtained at the orientation of $\alpha = 0^{o}$ in the horizontal plane, which is the most natural position not requiring divergence of the extremity.

Moreover, men obtained very good results at $\alpha = -30^{o}$ both in the vertical and horizontal planes (i.e. with the extremity oriented inwards or downwards), whereas women obtained better results at supination for $\alpha = +30^{o}$ also in the vertical and horizontal planes (i.e. with the extremity oriented outwards or upwards).

Conclusion

The resulting correlations are significant for the arrangement of the controlling components and devices. Utilisation of such data at the design phase of machines and control panels may contribute to a reduction of operator's physical effort and make the controlling process safer and more precise.

Based on the analysis of the correlations found, the best location of the control components requiring the application of turning force of the upper extremity (various knobs, rotating handles) is the horizontal plane on the operator's right side at the level of upper extremity in the normal position or with a small divergence. This is particularly important when it comes to components of high importance for the control or safety and those frequently used. If it is not possible to ensure such an arrangement, the extreme locations in the vertical plane at the operator's left side should be avoided.

The ergonomy of devices, machines and stationary work posts is determined by adopting appropriate guidelines at the design phase. The study

completed may be complementary to the existing data and guidelines and could contribute to the improvement of the existing work conditions concerning process control.

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