Mathematical Model and Analysis of Back and Abdominal Muscle Loading in Relation to Angle of Bending and External Load

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***Abstract* – The action of forces in the back and abdomen under conditions of loading of different external forces at different bending angles is unexplored area. This paper presents a methodology that enables calculation of the magnitudes of forces in the back and abdominal muscles using the combined techniques of the CATIA software system, appropriate mathematical model and polynomial regression analysis.**

The person of 180cm in height and 85 kg in weight is loaded with 5 + 5 kg of cargo in both hands, and three cases of bending angles of 15^0, 30^0 and 60^0 relative to the vertical axis are analysed.

***Keywords* – Ergonometrics, anthropometry, abdomen, CATIA - ergonomic modules.**

1. Introduction

Every part of the human body has its limited possibilities of action, and any changes that occur on the parts of the body should be monitored and analyzed for the necessary humanization of work [1].

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Damage that can occur to the body is a serious problem, and it can lead to disability and ultimately death. In this case of disagreement between the load of the body and its ability to endure, the organism has to adequately respond to these requests [4].

When designing jobs, it is necessary to analyze person's working conditions, as well as the machines and environments that surround it. This means that it is necessary to align technology, ergonomics and organization with the ultimate goal of achieving optimum performance [10]. In order to analyze all those conditions, it is necessary to know the anthropometric characteristics of the person performing the work task, as well as to know which parts of the body are active in function of performing the work process.

To determine the population of subjects whose body dimensions are registered, about 50 percent of them have a body reference size of a certain size or smaller. Therefore, it is necessary to know the dimensions of individuals as a function of statistical distribution [12].

The ergonomic module of CATIA software package was used to create a virtual respondent that is appropriate to the mathematical model. As a result of the biomechanical analysis, the values of the compression forces and torque in the L4-L5 zone of the model for the indicated bending angles were obtained. The maximum compression force is assumed to be 3.4 KN, which was previously established in the works of Morris and other authors [11].

2. Aim

The aim of the paper is to determine the load of the back and abdominal muscles at different angles regarding the bending of subjects, using the CATIA ergonomic module software package on the basis of new regression functions and virtual model movements.

Tests were conducted on a population of 50 subjects, using the average model with of 180cm in height and 85kg in weight.

3. Methods

To solve this problem, the beginning of work is based on the design of respondents according to the default average anthropological values in the software package CATIA-ergonomic module. The biomechanical analysis for the specified bending angles at a given load should be determined, and then the compression force (K) and the torque (M) in the L4-L5 zone should be determined [5].

As a hypothesis and connection with the bending angle, we will use the appropriate mathematical model as well as the values of compression forces and torque in the L4-L5 zone determined by CATIA analysis. Based on the mathematical model set, the values of the forces acting in the back and abdominal muscles of the body will be determined.

4. Results

In the first part of the paper, taking into account the established average anthropological values of the respondents, a corresponding virtual model in the CATIA software package was designed. The analysis was first performed in the case of a bending angle of the 15 degree model with respect to the vertical, with a load of 5 + 5kg in both hands. Figure 1 shows the height and weight of a person tuned into CATIA module for ergonomics and biomechanics.

At the beginning, we set the first position - a 15-degree bend in the lumbar region and a 5 + 5kg load in the arms (Fig. 1).

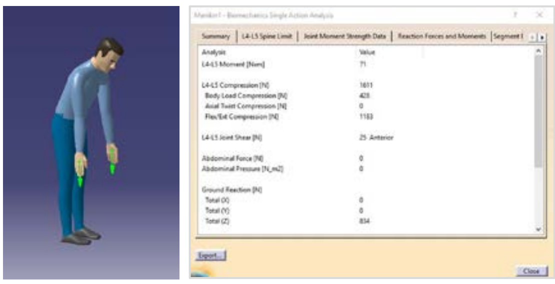

Figure 1. Model view for position 1 and its biomechanical analysis

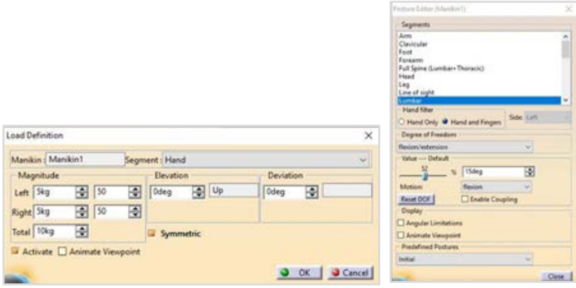

Figure 2. Values for arm loads and the angle of deflection in the lumbar region (position 1)

In the second part, the torque in the L4-L5 zone and the magnitude of the compression force in the L4-L5 zone are obtained for the known bending angle and the indicated lifting load (Fig. 2).

For position 2 the deflection is 30 degrees in the lumbar region, with the same load in the hands of 5 + 5kg each (Fig. 3).

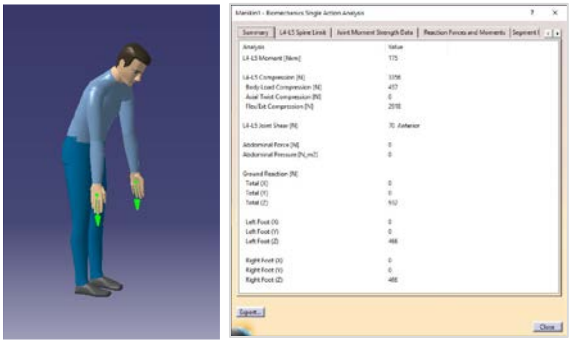

Figure 3. Model view for position 2 and its biomechanical analysis

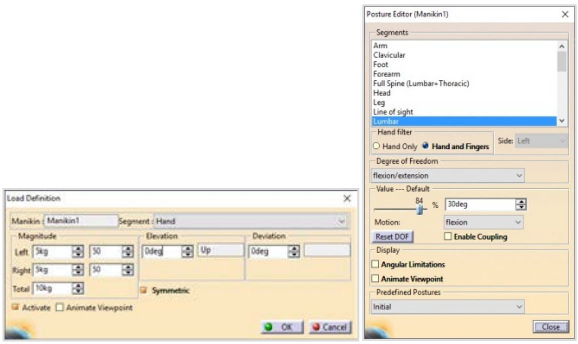

Figure 4. Values for arm loads and the angle of deflection in the lumbar region (position 2)

In the third position the deflection is 60 degree in the lumbar region, with the same load in both hands of 5 + 5kg (Fig. 5).

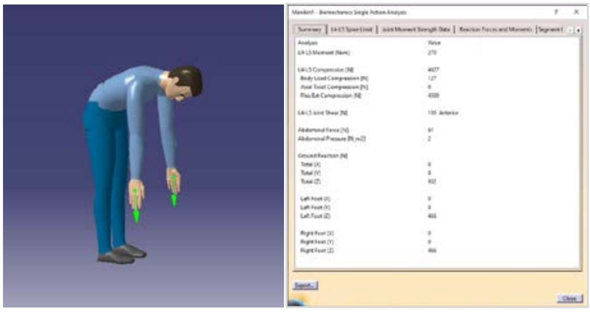

Figure 5. Model view for position 3 and its biomechanical analysis

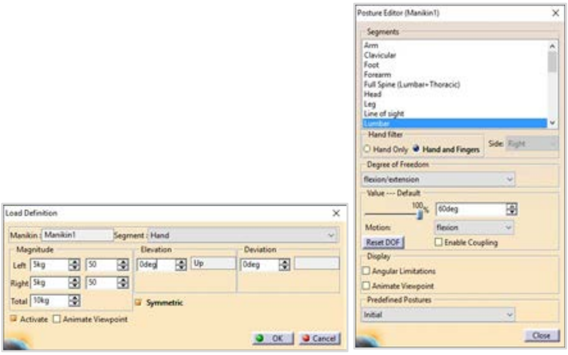

Figure 6. Values for arm loads and the angle of deflection in the lumbar region position 3)

The magnitudes of the moments and the compression forces in the L4-L5 zone for all three positions are presented in Table 1.

Table 1. Biomechanical analysis

Bending angle (^{0})	15^0	30^0	60^0
Moment L4-L5 (Nm)	71	175	270
Compression force (N)	1,611	3,356	4,627

In the second part, it is necessary to make an appropriate mathematical model of the placed respondent. In this sense, it is necessary to define the amounts of segmental body masses and loads in the hands of the model at first, as well as the distances of these forces with respect to the L4-L5 zone. For this determination, we will use the ratio analysis of the individual parts of the human body, shown in Figure 3. [12], [3]

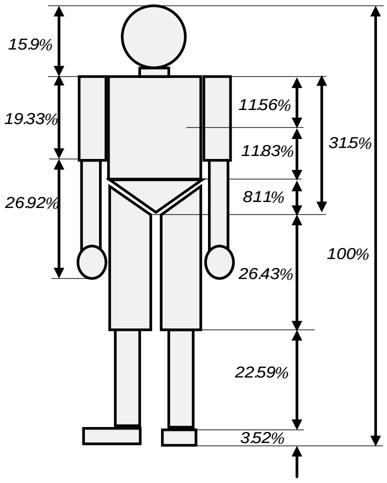

Figure 7. Distribution of model's segmental heights in percentages [12]

The total force acting on the body is divided into forces Q_1, Q_2 and Q_3. The force Q_1 is determined by the weight of head, upper arm, forearm, fist and load.

The force Q_2 is determined by the weight of the lower hull, while the force Q_3 is determined by the weight of the upper hull, the middle hull.

The values of the segmental masses will be determined by the methodology given by Donskoi and Zatsiorsky [2]:

$$M_o = m + B_0\, M + B_1\, h \;\; \text{[kg]} \qquad (1)$$

We will determine the segmental masses for individual body parts according to the relation (1), where m, B_0 and B_1 are regression factors, M is body weight and h is body height [6], [8]. Additionally, we will take into account the values for weights of individual body parts given in Table 2:

Table 2. Values of segmental masses

Weights [kg]							
head	upper arm	forearm	hand	upper torso	middle torso	lower hull	load
5,32	2,32	1,34	0,50	13,60	14,24	9,61	10

Q_1 = 5,3235 + 2,3234 + 1,3416 + 0,5045 + 10 = 9.5 kg + 10 kg = 19,5 kg = 195 N

Q_2 = 9.61 kg = 96 N

Q_3 =13.60 + 14.24 = 27.84 kg = 278 N

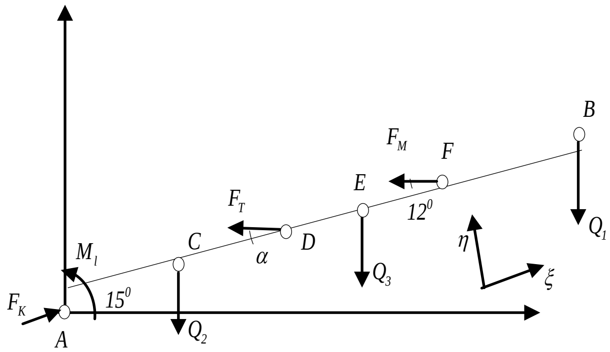

Figure 8. Mathematical model of subjects at an angle

From Figure 8 we get:

$\overline{AB} = 0.567\ (m)$, $\overline{AC} = 0.098\ (m)$, $\overline{AF} = 0.463\ (m)$, $\overline{AE} = 0.356\ (m)$, $\overline{AD} = 0.228\ (m)$
$Q_1 = 195\ (N)$, $Q_2 = 96\ (N)$ $Q_2 = 278\ (N)$ $F_k = 1611\ (N)$, $M_1 = 71\ (Nm)$

$$\sum \xi = 0:$$
$$F_k - F_T \cdot cos\alpha - F_M \cdot cos12^0 - (Q_1 + Q_2 + Q_3) \cdot cos15^0 = 0,$$
$$1611 - F_T \cdot cos\alpha - F_M \cdot 0.978 - (195 + 96 + 278) \cdot 0{,}965 = 0,$$
$$F_T \cdot cos\alpha + F_M \cdot 0.978 = 1{,}061.915 \qquad (2)$$

$$\sum \eta = 0:$$
$$F_T \cdot sin\alpha + F_M \cdot sin12^0 - (Q_1 + Q_2 + Q_3) \cdot sin15^0 = 0,$$
$$F_T \cdot sin\alpha + F_M \cdot 0.208 - (195 + 96 + 278) \cdot 0.258 = 0,$$
$$F_T \cdot sin\alpha + F_M \cdot 0.208 = 146.802 \qquad (3)$$

$$\sum M_A = 0:$$
$$M - Q_1 \cdot \overline{AB} \cdot cos15^0 - Q_2 \cdot \overline{AC} \cdot cos15^0 - Q_3 \cdot \overline{AE} \cdot cos15^0 + F_T \cdot \overline{AD} \cdot sin\alpha + F_M \cdot \overline{AF} \cdot sin12^0 = 0,$$
$$175 - 195 \cdot 0.567 \cdot 0{,}965 - 96 \cdot 0.098 \cdot 0{,}965 - 278 \cdot 0.356 \cdot 0{,}965 + F_T \cdot 0.228 \cdot sin\alpha + +F_M \cdot 0.463 \cdot 0.208 = 0,$$

$$F_T \cdot 0.228 \cdot sin\alpha + F_M \cdot 0.0963 = 36.278. \qquad (4)$$

Combining (3) and (4) we get $F_M = 57.520$. Incorporating the value for F_M into (2) and (3) we get that $tg\alpha = 0.134$, and therefore $\alpha = 7.636^0$.

Finally, from (1) we get
$F_T = 1{,}014.66$

Table 3. Values of ice and abdominal muscles depending on bending angle

Bending angle (^{0})	15^0	30^0	60^0
Force in upper back muscles (N)	57.52	-2,002.95	-4,618.75
Force in lower back muscles (N)	1,014.66	5,111.91	8,740.53
Force in abdominal muscles (N)	338.22	1,703.97	2,913.51

Using the values from Table 3, we applied a polynomial regression in order to fit a polynomial equation of a second-order to data. Relationship between the independent variable x (bending angle) and dependent variable y (force in upper back muscles) can be approximates as

$$y = b_0 + b_1 x + b_2 x^2,$$

in which y_i is predicted outcome value for the polynomial model. b_0, b_1 and b_2 are regression coefficients which can be determined mathematically by minimizing the sum of squares or residual (R)

$$R^2 = \sum_{i=1}^{n} [y - (a_0 + a_1 x + a_2 x^2 + \dots + a_k x^k)]^2$$

Using Excel's built-in functions '*minverse*' and '*mmult*' the above problem can be easily solved in an interactive manner. In this particular case we use Excel's capability to perform a multiple regression analysis using a second order polynomial (quadratic curves) by adding a '*trendline*' and scatter plot graphical tool to the data. The result is shown in Fig. 9, 10 and 11 for forces in upper back, lower back and abdominal muscles.

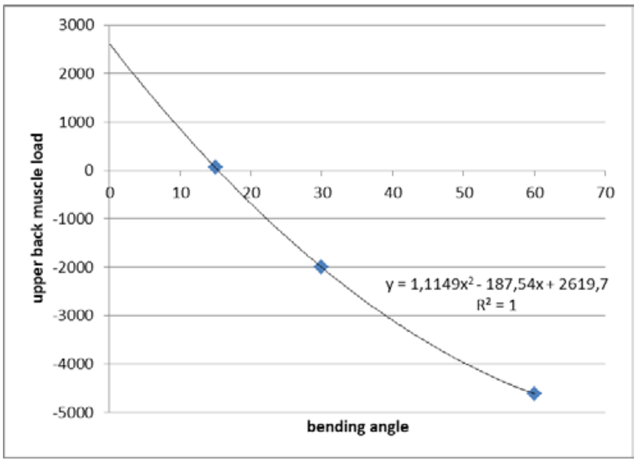

Figure 9. Distribution of forces in upper back muscles as a function of bending angle

Based on the regression function (Fig. 9), we find that the critical stress angle of the upper back muscles is $\alpha_{critical} = 15.38^0$.

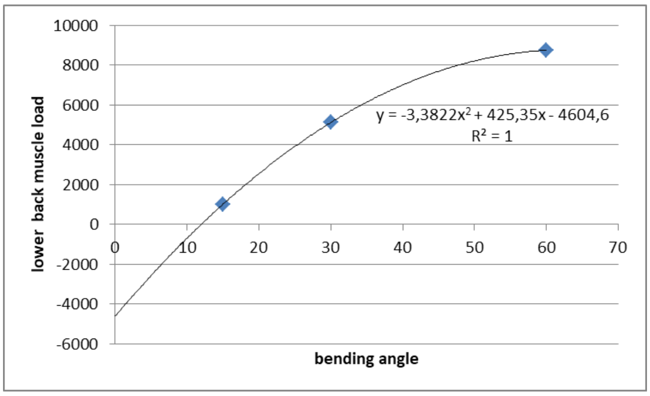

Figure 10. Distribution of forces in lower back muscles as a function of bending angle

Based on the regression function (Fig. 10), we find that the critical stress angle of the lower back muscles is $\alpha_{critical} = 11.96^0$. We note that in reference [10] the size of the abdominal muscles is one-third of the lower back muscles.

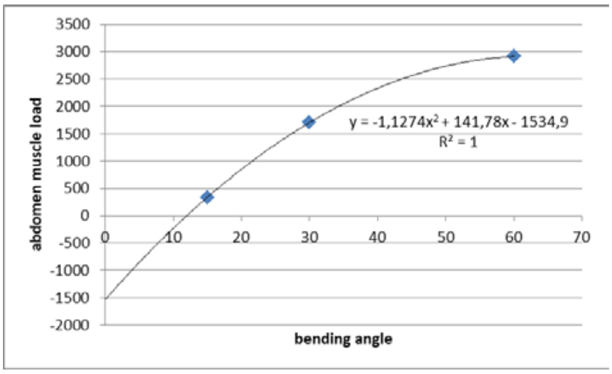

Figure 11. Distribution of forces in abdominal muscles as a function of bending angle

Based on the regression function (Fig. 11), we find that the critical stress angle of the abdominal muscles is $\alpha_{critical} = 11.96^0$.

5. Conclusion

Back pain is one of the most common problems that occur as a result of physical inactivity and a predominantly sedentary lifestyle. It is estimated that 80% of the population experience low back pain during their lives, which is accompanied by decreased ability to work and difficult activities from a daily life. Problems most commonly occur between the ages of 30 and 50, reflecting an unhealthy lifestyle and disrupting proper musculoskeletal relationships. The most common reason for the onset of lumbar pain syndrome is the decreased lumbar stability that occurs as a result of muscle weakness due to physical inactivity and consequently poor posture and poor biomechanics of movement [7], [9].

Using the CATIA ergonomic module as well as the regression polynomial analysis of the mathematical model, the values for the critical stress angles of the upper, lower and abdominal back muscles were determined. The results obtained form the basis for an individual approach to biomechanical studies of human activity and enable personalization of investigations regarding the dynamic anthropometric features.

References

[1]. Arokoski, J. P., Valta, T., Airaksinen, O., & Kankaanpää, M. (2001). Back and abdominal muscle function during stabilization exercises. *Archives of physical medicine and rehabilitation*, *82*(8), 1089-1098.

[2]. Donskij, D. D., Zacijorskij, V. M. (1979). Biomehanika, Moskva,*Izdateljstvo Fizkultura i sport*.

[3]. Knight, I. B., & Eldridge, J. (1984). *The heights and weights of adults in Great Britain: Report of a survey carried out on behalf of the Department of Health and Social Security covering adults aged 16-64* (Vol. 1138). HM Stationery Office.

[4]. Elbert, K. K., Kroemer, H. B., & Hoffman, A. D. K. (2018). *Ergonomics: how to design for ease and efficiency*. Academic Press.

[5]. Mairiaux, P., Davis, P. R., Stubbs, D. A., & Baty, D. (1984). Relation between intra-abdominal pressure and lumbar moments when lifting weights in the erect posture. *Ergonomics*, *27*(8), 883-894.

[6]. Callaghan, J. P., & McGILL, S. M. (2001). Low back joint loading and kinematics during standing and unsupported sitting. *Ergonomics*, *44*(3), 280-294.

[7]. Gardner-Morse, M. G., & Stokes, I. A. (1998). The effects of abdominal muscle coactivation on lumbar spine stability. *Spine*, *23*(1), 86-91.

[8]. Chaffin, D. B. (1988). Biomechanical modelling of the low back during load lifting. *Ergonomics*, *31*(5), 685-697.

[9]. Stokes, I. A., Gardner-Morse, M. G., & Henry, S. M. (2010). Intra-abdominal pressure and abdominal wall muscular function: Spinal unloading mechanism. *Clinical Biomechanics*, *25*(9), 859-866.

[10]. Hoozemans, M. J., Kuijer, P. P. F., Kingma, I., van Dieën, J. H., de Vries, W. H., van der Woude, L. H., ... & Frings-Dresen, M. H. (2004). Mechanical loading of the low back and shoulders during pushing and pulling activities. *Ergonomics*, *47*(1), 1-18.

[11]. Morris, J. M., Lucas, D. B., & Bresler, B. (1961). Role of the trunk in stability of the spine. *JBJS*, *43*(3), 327-351.

[12]. Veljović F. (2007). Biomehatronika, University of Sarajevo, Faculty of Mechanical Engineering, University book.