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EXTENSIVE BIOMECHANICAL ANALYSIS OF PASSENGER LOCOMOTION IN AIRBUS A320

ABSTRACT

Every human working activity is related to adequate workload and therefore also stress. The workloads of people working in different working postures form a wide but still insufficiently studied biomechanical and ergonomic field. Carrying, lifting and manipulating freight often results in relatively high loads, and in case of the need for increased frequency of such procedures, the result is an exhausting dynamic strain of the human body. The loads that can occur during human activities are in the majority of cases related to their extremely non-ergonomic working position. It has been determined that the working postures of the human body are supported by the action of the muscle system on the human locomotoric chain. Non-ergonomic posture of human body is harmful, especially in case when it is forced or when it is in the field of suboptimal condition. High loads affect directly the human safety, and in case of longer exposure of the body to the action of such loads, the possibility for more permanent organism damages of organism may occur.

KEY WORDS

computer anthropometry, biomechanics, ergonomics, scientific visualisation of humanoid models

1. INTRODUCTION

From the earliest times of human scientific history, the researchers were fascinated by the capabilities of human locomotion. At the beginning of the 20th century, the advent of computer technologies brought about sudden increase in the study of human motion. The pioneers of bio-mechanical research work, such as Marey, Muybridge, Braune, Fischer and others based their scientific work precisely on the development of new technologies. In 1950s the advent of instruments that facilitated high-speed photography, and usage of the possibilities of digital manipulation and processing of the collected material resulted in opening of new scientific levels of study of human locomotion.

The past biplane analyses of human motion were simplified as segmental analyses of two-dimensional projections of different space planes (sagital, frontal, etc.); with SABA*Lab* approach the actual 3D analysis will be done, of the movements which include the overall morphology and asymmetry of the human body movements during the working activity. The paper presents the statistical anthropometric analysis of the assumed population in Croatia, and it has been furthermore, based on the similarity, compared to the anthropomeasures given by Kroemer for the German population where the measures were carried out on more than 15,000 male and female subjects.

In the existing and available literature there is a large number of descriptions regarding research during the design of operating environmental systems, that often even besides their great picturesqueness and all their logic anthropometric connectivity are not on the trail of calculating the human effort, i.e. assessing the workload. Thus, e.g. from the anthropometric analysis of the scope of movements, as often found in literature related to the problems of workplace design, the defined space dimensions appear, as well as the descriptions of the reach of limbs, and very often the data are also mentioned regarding the possible comfort or discomfort. However, from these data you cannot observe any numerical indicators on the values of forces or their duration and reaction of the human body to them.

Since the primary task of optimization by reduction of the human workload consists in adapting the physical conditions of work to psycho-physiological and bio-morphological properties of humans, it is necessary to find such procedure of operation which is maximally suitable to the human properties. These properties are considered through its structural and bio-mechanical characteristics that in working processes occupy a certain vital space. Computer 3D biomechanical anthropometrics enables finding the necessary data and interpretation of certain results regarding the morphological properties of human factors within the complex system of humans and their respective environmental systems [1].

2. 3D MECHANICAL ANALYSIS OF BIOLOGICAL HUMANOID SYSTEMS

The study of biomechanical anthropometry studies the segmental masses of individual body parts as well as their space distribution within the selected coordinate system. It furthermore studies the dynamic moments of inertia reduced to the mass centres both of the individual body segments and of the common centre of masses. Regarding their different meanings in relation to the static and kinematic value anthropomeasures the mentioned groups of biomechanical anthropomeasures are called dynamic anthropometry. Regarding the dynamic characteristics of human body during performing of various activities, it is especially important in the studies of dynamic anthropomeasures to pay attention to defining the time determinants of these values during the working process.

During the analyses of human body movements, or for relative movements of its single parts with the presence of relatively high accelerations, it is necessary to know the forces and moments, speeds and accelerations of single anthropometric body points, then the posture of mass centres, and dynamic inertia moments, both of single parts as well as of the whole body at the observed moment. Regarding the mentioned, the dynamic anthropomeasures are divided into external and internal ones. Thus, in the example of human body, the dynamic inertia moments of single segments are determined by external limits of these environments and are called external dynamic inertia moments. Since masses are also included in the relative movements of body segments, and as they do not refer only to external limits of single segments, the term internal dynamic inertia moments is introduced and these are dependent on the relative position of the studied body segment. Regarding the complexity of the biomechanical structure of the human body, this type of dynamic values has still been insufficiently studied. A recognizable example of the action of internal dynamic inertia moments is the raising of the arm from the lowered position of a standing person. In the initial time during the movement of the arm, only the mass of the limb determined by its outer borders can be taken into consideration, but after a certain change of posture, the mentioned action starts to include also the breast and back muscles resulting in the motion which includes the change of mass of the studied segmental system.

Determination of the mass distribution in humans as well as the position of the centre of gravity was the subject of research of Fisher and Braun from 1889. They determined an approximate method, which is known as the Method of Coefficients. The Method assumes direct functional connection between the length of the body segment with its mass. The mentioned scientists used these relations to solve the position of the centre of gravity, inertia radius and dynamic inertia moment.

Significantly more accurate results were determined by Dempster in 1955 dividing the body segments in a way which is also acceptable and common in anthropometry today. For these measurements Dempster designed a special type of vessels into which the examinees immersed single body segments as presented in Figure 1.

Based on the volume of displaced water the volume of the observed segment was determined. The figure shows in schematic form the design of these vessels, as well as the adequate method of measuring the volume of single body segments. Thus, e.g. in order to determine the volume of the arm, first the volume of the displaced liquid for the hand is determined, then the hand and forearm are immersed to determine their joint volume and finally this is done for the whole arm. It follows that the volume of the upper arm, and consequently of all the other segmental body parts can be determined by simple subtraction of the volume of forearm and hand from the volume of the whole arm [2].

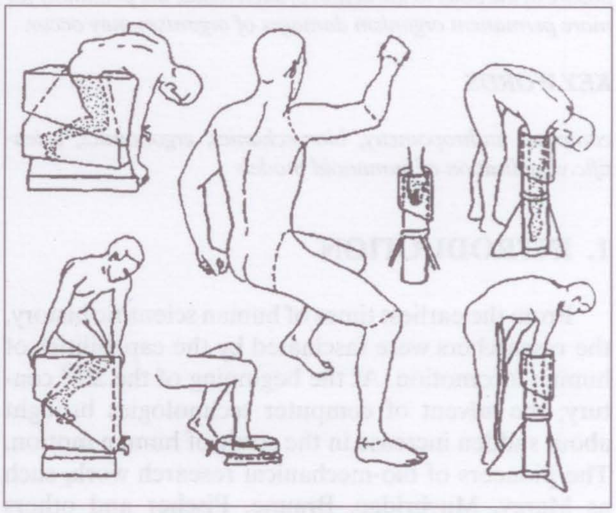

Figure 1 – Dempster's vessels for determining the volume of the human body parts

The scientists of biological anthropology not satisfied with such relatively imprecise results have started to look for new and more precise methods of determining the segmental masses of body parts. One of such advanced methods for determining the mass distribution and dynamic characters of body segments is the radioisotope method of Donskij and Zacijorskij. From the statistical processing of the results determined in this way, the authors have defined for each segmental part the regression lines and determined adequate approximation coefficients which can be used to calculate the desired masses [3].

Segment masses according to them are calculated by means of the following regression equation:

$$m_i = B_0 + B_1 \cdot M + B_2 \cdot h \qquad (1)$$

where:

m_i – mass of the analyzed segment (kg),
$B_0\,B_1\,B_2$ – regression coefficients (kg),
M – total subject mass (kg),
h – standing subject height (cm).

During the development of anthropometric science various methods were being found in order to determine from the standing tallness of the humans and their total body weight, all the other values of the human body parts. This had to lead to searching for suitable connections from human harmony and canons of human body structure.

General results of harmonic analysis applied to humans have proven as functions of anthropometric values in dependence on the standing tallness of humans, i.e. in the example when h = 2R, then the relations presented in Table 1 are valid [4].

Table 1 – Segmental lengths of humans as function of tallness

Arm length = (25 / 84) h	Upper arm length = (5 / 32) h
Forearm length = h / 8	Hand length = (97 / 64) h
Leg length = (17 / 32) h	Upper leg length = (9 / 32) h
Lower leg length = (7 / 32) h	Foot length = (1 / 32) h

In compliance with functional segmental lengths of the human body height there are considerations [4] that the so-called harmonic circle is used to define the relations of the body part lengths. For the mentioned anthropometric analysis the Greek canon of eight head heights is used, and it indicates that the total presented body tallness of the human corresponds to the sum of eight head heights.

When this canon is associated to the harmonic circle the grid construction is possible, and it indicates the human contour borders, as presented in Figure 2. Connections between radii of harmonic circle R and values a and b are the following:

$$a = 1; \quad R = \frac{\sqrt{5}}{2}; \quad b = \frac{\sqrt{2}}{2} \qquad (2)$$

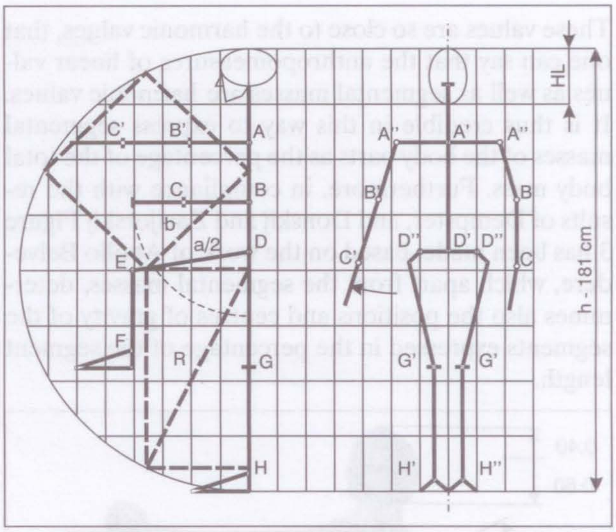

Figure 2 – Harmonic circle with associated grid of eight head heights canon and with plane model of geometrical human skeleton

and the harmonic values have been deduced:

$$r = \frac{\sqrt{2}-1}{2} = b - \frac{a}{2},$$
$$d = \frac{\sqrt{5}-1}{2} = R - \frac{a}{2}, \qquad (3)$$
$$b + r = \frac{2\sqrt{2}-1}{2}.$$

The next step of harmonic analysis refers to determination of mass distribution of external divided segments comparing them with the total body mass. Table 2 presents the values of segmental masses, as relative values of segments masses versus part of the entire body mass.

Table 2 – Body segment masses compared to the total body mass

Body segment		Relative value of mass (%)		Harmonic numbers for radius R = 11
Head		6.94		b = 6.95
Trunk	upper part	15.956	43.457	4a + (r+d) / 2 = 43.415
	middle part	16.327		
	lower part	11.174		
Arm	upper arm	2.707	4.963	a / 2 = 4.963
	forearm	1.615		
	hand	0.614		
Leg	upper leg	14.165	19.866	2 a = 19.68
	lower leg	4.330		
	foot	1.371		

It results from the carried out analysis of relative values of the body part masses that the distribution of segmental masses of an adult humanoid, either female or male, is in compliance with the harmonic numbers.

These values are so close to the harmonic values, that one can say that the anthropomeasures of linear values as well as segmental masses are harmonic values. It is thus credible in this way to express segmental masses of the body parts as the percentage of the total body mass. Furthermore, in compliance with the results of Dempster, and Donskij and Zacijorskij Figure 3 has been made, based on the work of Apollo Belvedere, which apart from the segmental masses, determines also the positions and centres of gravity of the segments expressed in the percentage of the segment length.

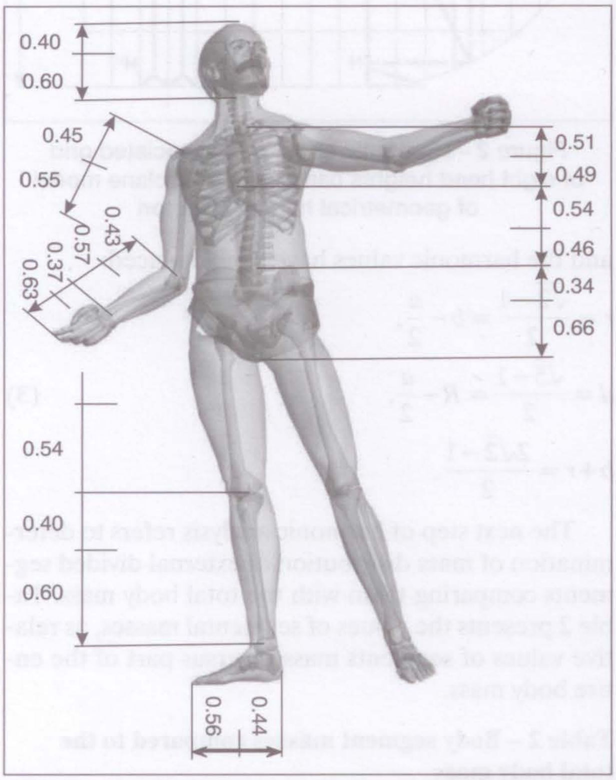

Figure 3 - Relative position of the centres of masses of the body parts in humans

Related to the principally dynamic character of human activities, it is necessary to study also the values on dynamic characteristics of body dimensions, i.e. to determine the information on the correlations of the anthropometric factors related to the movement dynamics in performing complex working activities. This is also the origin of the needs to find biomechanical values of kinetic body chains, all related to different body postures.

3. BIOMECHANICAL 3D HUMANOID MODELS

The biomechanical model should encompass maximum number of degrees of freedom of movement and simulate as best as possible with its characteristics the actual state. The most suitable is the kinematic chain model in which the joints are connections between single model segments. In the analysis and simulation of movement the geometric and inertia characteristics of body segments [5] have great influence. Figure 4 shows the wire biomechanical model within SABA roentgenogram body contour of the examinee in Kroemer anthropometric posture.

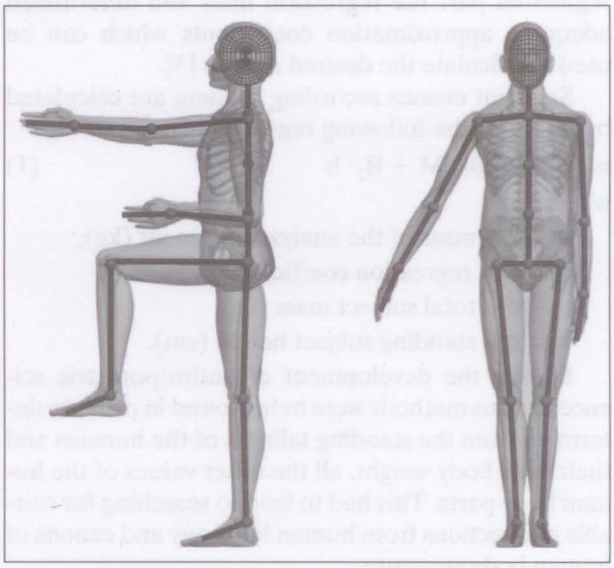

Figure 4 – SABA biomechanical model of the examinee

In modelling the human body segments by geometric shapes certain assumptions and simplifications need to be introduced. Human body consists of heterogeneous material and its properties are different for different parts. Besides, there are differences in the segment masses while moving regarding the different number of the groups of muscles which participate in performing the movement of single body segments, and principally belong to other segments. In spite of the mentioned characteristics, it is assumed that the segments are solid bodies interconnected by joints.

Also, uniform density per lateral cross-section as well as along the longitudinal segment axis has been assumed, whereas average segment densities have been taken from literature. The following assumption is the symmetry of the body structure in order to obtain symmetric values for the left and right limbs. In designing the trunk, in principle the symmetry has been adopted in which the central sagital plane divides he body into symmetric left and right side, and the central frontal plane into symmetric front and back part, so that the trunk is designed by symmetric geometric solid regarding the sagital and frontal plane.

In principle, recognizing the mentioned assumptions and simplifications, the solids of virtual biomechanical models are designed with 16 geometric solids connected by joints. The solid is divided into segments by planes perpendicular to the longitudinal axes of the segments in a way defined by Donskij and Zacijorskij, which enabled the use of their data to determine the position of the mass centres of single body segments and the regression equations to determine the segmental masses.

Head and neck are considered one segment, and they are separated from the upper part of the trunk by a plane perpendicular to the longitudinal axis of the head which passes through the throat hole (suprasternale). The trunk is divided into three parts – upper, middle and lower part, i.e. thorax, abdomen and pelvis. The plane which represents the border between the thorax and abdomen passes through the peak of the breast bone, and the abdomen and the pelvis are separated by a plane which passes through the navel. Pelvis stretches from the navel to the hip-joints. The segments of upper and lower limbs are determined by dividing the limbs in the joints by planes that are perpendicular to the longitudinal axes of the segments. The upper leg stretches from the hip-joint to the knee joint, the lower leg from the knee to the ankle, and the ankle represents the border between the lower leg and foot. The arm is divided into upper arm, forearm and hand, with borders in the shoulder joint, elbow and wrist.

Regarding previous biomechanical assumptions of the degrees of freedom of movement of the 3D humanoid model, it is possible to define the structural scheme as a kinematic chain. The structural scheme of the human skeleton is taken as a system which consists of one closed kinematic chain of the spine with the thorax and five open kinematic chains: head, arms and legs. The mobility of the system can be defined by means of the degrees of freedom of movement, and this is significant regarding the possible reductions to a reasonable extent in order to develop various research approaches. Another useful reason of knowing the degrees of freedom of movement is the possibility of defining the mathematical synergy, single parts of the organism, both for theoretical and practical reasons.

The structural scheme of the human skeleton has a very large number of degrees of freedom of movement. Since the human skeleton consists of: 95 joints with one degree of freedom of movement, 80 joints with two degrees of freedom of movement, and 75 joints with three degrees of freedom of movement, which gives a total of 250 degrees of freedom of movement. Out of these, 28 degrees of freedom of movement are accounted for by the upper limb of the arm, and 25 degrees of freedom of movement to the lower limb of a leg, which means that 106 degrees of freedom of movement are accounted for by the upper and lower limbs, which is about 40% from the total number of the degrees of freedom of movement. The spine contains 54 degrees of freedom of movement or about 20% of the total number. The remaining 40% of degrees of freedom of movement of the human body are accounted for by the joints of the thorax, neck and head. Consequently, all the complexity of the kinematic and dynamic study of the human skeleton within the implementation into the computer designed 3D humanoid models is understandable.

By introducing the computers and 3D software solutions, the examinee can be replaced by a computer-generated 3D model, which can be used to perform interactively all the necessary designs and changes in real time.

The development of a biomechanical model of the human body requires basic preparation and analysis of every single segment contained in the human body. This means that the authenticity of presentation of the human body depends on the in-advance defined number of cross-sections, in which the body segments need to be divided into smaller parts.

4. EXPERIMENTAL PART

The introductory research of determining the biomechanical values for the assessment of the locomotion of human activities of the studied measurement entity and dimensions of the observed working procedure of placing a travel bag into its proper place within Airbus A320 commercial aircraft, was performed within the real aircraft environment at the airport Pleso (Zagreb), in laboratory conditions at the Faculty of Physical Education (Zagreb), and the computer laboratory SABALab (Čakovec).

Figure 5 gives a presentation of determining the lumbar moment due to the action of external load for the isolated characteristic posture of work action

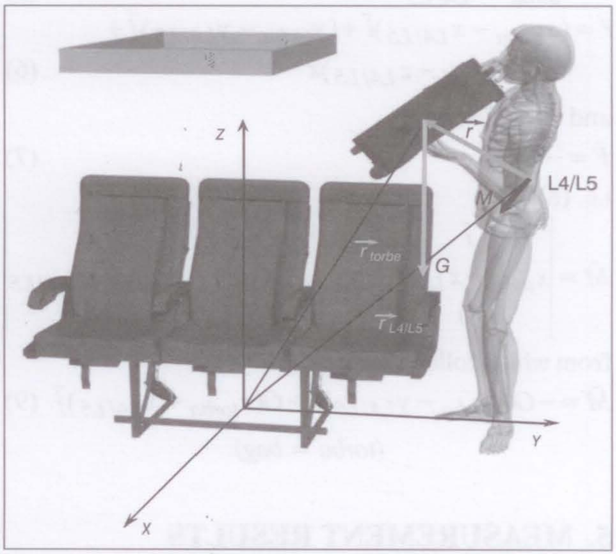

Figure 5 – Roentgenogram virtual 3D biomechanical model of the examinee with plotted direction of action of moment M on the selected critical point 0 (L4/L5)

Table 3 - Tabular presentation of mass centre calculation

Body segment	m_i	x_i	y_i	z_i	$m_i \cdot x_i$	$m_i \cdot y_i$	$m_i \cdot z_i$
Head	5.2069	446.09	167.68	203.79	2322.76	873.09	1061.11
L upper arm	1.9794	451.10	132.78	201.52	892.90	262.83	398.88
R upper arm	1.9794	418.07	158.09	202.88	827.51	312.93	401.57
L forearm	1.1769	443.21	120.50	193.64	521.61	141.81	227.89
R forearm	1.1769	410.40	162.31	198.69	483.00	191.02	233.83
L hand	0.4737	438.38	128.99	171.06	207.64	61.10	81.02
R hand	0.4737	430.60	158.45	185.35	203.95	75.05	87.79
Upper trunk	11.2632	439.72	145.90	200.78	4952.61	1643.24	2261.43
Middle trunk	11.4471	433.38	130.69	197.46	4960.97	1495.98	2260.29
Lower trunk	8.7820	429.24	114.42	195.77	3769.54	1004.81	1719.23
L upper leg	10.5119	435.41	75.01	192.16	4576.95	788.48	2020.00
R upper leg	10.5119	419.42	75.01	188.05	4408.89	788.53	1976.74
L lower leg	2.9856	432.61	35.01	192.64	1291.61	104.53	575.14
R lower leg	2.9856	420.68	35.42	184.30	1256.00	105.74	550.26
L foot	1.0913	435.60	2.47	196.47	475.37	2.70	214.40
R foot	1.0913	420.03	2.50	182.71	458.38	2.72	199.39
Total:	73.1367				31609.69	7854.55	14268.99

within the acting group of lifting the travel bag in the passenger cabin of Airbus A320 aircraft. The same method is used to determine also the moments of the weight forces of each single segment regarding the critical point L4/L5, as presented in expressions 4 – 9.

where:

$$\vec{M} = \vec{r} \times \vec{F} \tag{4}$$

where:

$$\vec{r} = \vec{r}_{torba} - \vec{r}_{L4/L5} \tag{5}$$

$$\vec{r} = (x_{torba} - x_{L4/L5})\vec{i} + (y_{torba} - y_{L4/L5})\vec{j} + \\ +(z_{torba} - z_{L4/L5})\vec{k} \tag{6}$$

and

$$\vec{F} = -G\vec{k} \tag{7}$$

i.e. (8):

$$\vec{M} = \begin{vmatrix} \vec{i} & \vec{j} & \vec{k} \\ x_{torba} - x_{L4/L5} & y_{torba} - y_{L4/L5} & z_{torba} - z_{L4/L5} \\ 0 & 0 & -G \end{vmatrix}$$

from which follows that:

$$\vec{M} = -G(y_{torba} - y_{L4/L5})\vec{i} + G(x_{torba} - x_{L4/L5})\vec{j} \tag{9}$$

$$(torba = bag)$$

5. MEASUREMENT RESULTS

The centres of masses of individual body segments and the total centre of mass have been determined on a virtual 3D humanoid model of examinees within a computer-generated associated environmental system of the passenger cabin of aircraft Airbus A320, as seen from Table 3.

6. ANALYSIS OF MEASUREMENT RESULTS

Table 4 shows the calculation of the reduced dynamic inertia moments, and Table 5 gives a presentation of the values of moments around point 0 of the lumbar part of the spine (L4/L5).

$X_T = \Sigma X_i \cdot m_i / M = 432.20$cm;

$Y_T = \Sigma Y_i \cdot m_i / M = 107.40$cm;

$Z_T = \Sigma Z_i \cdot m_i / M = 195.10$cm.

7. CONCLUSION

The conducted anthropometric and biomechanical research of human activities during travelling not only by plane but also by other transport means, enables the design of exact and reliable virtual, digitally generated computer humanoid models and respective environmental systems for CAVEA (Computer Aided Virtual Ergonomic Analyses) researches of complex physical movements of humans.

The measurement results indicate the accuracy of using stick models within the cases of biomechanical

Table 4 - Tabular presentation of calculations of reduced dynamic inertia moments

Body segment	m_i (kg)	I_z ($kgcm^2$)	a^2 (cm)	Izt ($kgcm^2$)
Head	5.21	287.45	3827.13	20214.94
L upper arm	1.98	148.77	1001.82	2131.76
R upper arm	1.98	148.77	2770.04	5631.74
L forearm	1.18	70.07	292.83	414.70
R forearm	1.18	70.07	3490.43	4177.96
L hand	0.47	8.70	504.66	247.74
R hand	0.47	8.70	2609.35	1244.62
Upper trunk	11.26	868.66	1538.71	18199.48
Middle trunk	11.45	801.16	543.85	7026.67
Lower trunk	8.78	451.26	58.09	961.44
L upper leg	10.51	1960.08	1059.23	13094.58
R upper leg	10.51	1960.08	1211.97	14700.20
L lower leg	2.99	496.48	5239.66	16140.23
R lower leg	2.99	496.48	5313.76	16361.47
L foot	1.09	67.54	11020.71	12094.44
R foot	1.09	67.54	11152.06	12237.78
Iz = SIzt:				144879.75

Table 5 – Tabular presentation of calculating the values of lumbar moments

Body segment	m_i (kg)	d (cm)	F (N)	M (Nm)
Head	5.21	18.55	51.08	9.48
L upper arm	1.98	23.34	19.42	4.53
R upper arm	1.98	9.91	19.42	1.92
L forearm	1.18	17.06	11.55	1.97
R forearm	1.18	17.51	11.55	2.02
L hand	0.47	31.66	4.65	1.47
R hand	0.47	15.80	4.65	0.73
Upper trunk	11.26	11.95	110.49	13.20
Middle trunk	11.45	6.58	112.30	7.39
Lower trunk	8.78	5.33	86.15	4.59
Load	10.00	36.65	98.10	35.96

analyses, whereas space, digitally generated SABA roentgenogram humanoid models are more suitable for the ergonomic-biomechanical modelling, regarding the combination of the numerical simplicity of stick models with the characteristics of Kroemer space humanoid entities.

The introduction of computers and computer 3D software solutions have resulted in obtaining of virtual humanoid models and digitally generated accompanying environmental systems, on which all the necessary ergonomic designs and changes can be made. With the application of such CAVEA research within the traffic environment the harmony of dimensions of the environmental traffic systems and the human body can be established and determined, as well as their biomechanical and ergonomically correct postures and movements.

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SAŽETAK

3D BIOMEHANIČKA ANALIZA LOKOMOCIJE PUTNIKA UNUTAR ZRAKOPLOVA AIRBUS A320

Svaka ljudska radna aktivnost povezana je s odgovarajućim radnim opterećenjima a samim time i naporom. Opterećenja ljudi u različitim radnim položajima, čine široko i još uvijek nedovoljno istraženo biomehaničko i ergonomijsko područje. Prenošenje, podizanje i manipulacija teretom često rezultira relativno velikim opterećenjima, a ako se javlja potreba za povećanom učestalošću takvih postupaka, rezultat je iscrpljujuće dinamičko naprezanje čovjekova tijela. Opterećenja koja se mogu pojaviti tijekom ljudskog rada u većini slučajeva su povezana s njegovim izrazito neergonomskim radnim položajem. Utvrđeno je, da su radni položaji ljudskog tijela podržavani djelovanjem mišićnog sustava na lokomotorni lanac čovjeka. Neergonomski je položaj tijela čovjeka štetan, a naročito u slučaju kada je prisilan ili kada je u području suboptimalnog stanja. Velika opterećenja izravno utječu na sigurnost ljudi, a duljim izlaganjem tijela djelovanju takvih opterećenja otvara se mogućnost trajnijih oštećenja organizma.

KLJUČNE RIJEČI

računalna antropometrija, biomehanika, ergonomija, znanstvena vizualizacija humanoidnih modela

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