A QUATITATIVE APPROACH FOR ESTABLISHING SAFE WEIGHT OF LIFT

Salami O. ISMAILA[1] – Oliver E. CHARLES-OWABA[2]

Abstract: *The objective of this work was to formulate a mathematical model for predicting a safe weight of lift. Considering the intratruncal pressure, post-work height shrinkage of the worker and strain energy of the intervertebral disc, the SWL function was derived in terms of the Young Modulus of elasticity (E) of the articular cartilage (endplate of the disc); velocity of lift (u); acceleration due to gravity (g); vertical location of the load (V); horizontal length of the load from the ankles (H); vertical displacement of the load (D); the angle of lift (θ) and the lifter's anthropometric dimensions. To evaluate the function for a particular individual, the value of the length of the spine from the first thoracic to the last lumbar vertebrae, the heights just before the start and after the close of work were measured to determine the height shrinkage. Additionally, the breadth and depth of the trunk were measured. A range of values of the function parameters: V, H and D were adopted from National Institute for Occupational Safety and Health (NIOSH), while E and U were also taken from the literature. SWL values were computed and compared to those of the Recommended Weight Limit (RWL) of NIOSH and Maximum Acceptable Weight of Lift (MAWL) from the literature. At an average height shrinkage of 0.014 m and a maximum permissible shrinkage of 0.21 m, the SWL and* SWL_{Max} *values were significantly different (at 95% level confidence) from the corresponding RWL and the MAWL values.*

Keywords: – height shrinkage
– manual lifting
– safe weight of lift
– strain energy

1. INTRODUCTION

Manual materials handling (MMH) still exists in all facets of human endeavors, including the industries particularly in third world countries, despite the widely reported automation. MMH activities, which include lifting, placing, carrying, holding, and lowering, contribute to accidents and health hazards [1].

The analysis of compensation claims by workers shows that Manual Materials Handling was responsible for 32 % of workers' injuries and illnesses and 36 percent of costs [2, 3]. Similarly, [4] illustrates that injuries to the lower back, which include the lumbar and lumbo-sacral spine injuries, accounted for 29,5 % of Manual Materials Handling injuries and 41,6 % of cost claims. They also established that strain to the lower back area accounted for 27,2 % of MMH injuries, this representing 37,9 % of cost claims.

The above suggests that lower back injuries caused by lifting are major industrial problems worldwide, the source of perennial agony to several workers, and financial drain to industry. Hence, the situation calls for investigations into how lifting tasks can be scientifically designed to reduce or eliminate incidence of back injuries.

In 1962 the International Labour Organisation (ILO) published an information sheet, which specified limits for occasional lifting. These limits were set based on inspection of injury and illness statistics [5].

There has been quite a number of research works since 1962, when the limits were established by ILO to reduce injuries, especially low back pain associated with manual load lifting.

Three main approaches to determine what load to lift to minimize load lifting related to back injuries have been reported in the literature: Psychophysical [6-11]; Physiological [12,13] and Biomechanical [14, 15].

The widely celebrated models were the Practices Guide for Manual Lifting by NIOSH termed the Action Limit which was reviewed and renamed the 1991 NIOSH equation and termed the Recommended Weight Limit (RWL); and also the Maximum Acceptable Weight Limit (MAWL). The RWL was popular not only because it provided the health practitioners with an empirical method of computing a weight limit for manual lifting but also because MAWL being subjective was suggested to be replaced with more objective method whenever available [7].

Though there are many manual lifting models, they seem to have limited applications due to uncertainties in the existing scientific studies and theoretical models [16]. Moreover, the models seem too general to be selectively used to perfectly match individuals to industrial tasks for safety and higher productivity.

Hence, the objective of this paper is to propose a mathematical model to estimate the safe weight of lift using spinal shrinkage, NIOSH specified task parameters, some strain properties of the spine and some anthropometric dimensions of an individual.

2. METHODOLOGY

2.1. Model Development

The formulation of the model is based on the following assumptions:

1. The spine is the most important aspect of the lifting structure and therefore it is given serious consideration [17, 18]

2. Each of the endplate of the spine consists of hyaline and fibro cartilage [19] and may be modeled as an isotonic elastic material [20].

3. The lift angle is the angle between the horizontal line and the one drawn from the center of the spine to meet the horizontal line at the fifth lumbar (L5) (see Figure 2). [21] uses similar reasoning but named it the trunk angle.

4. The velocity of lift is 0,35 m/s [22].

5. An Elliptical truncal cross sectional area of the human subject is assumed to be as shown in Figure 1[23].

Elliptical Truncal Area, $A = \frac{\pi l_f l_s}{4}$ [24].

where l_f is the chest breadth measured across the chest at the nipple; l_s is the chest depth measured at the chest from front (sternum) to back(spinal groove).

6. The Modulus of elasticity of articular cartilage is assumed to be 2,4 MN/m^2 [25].

7. The strain energy at the spine is the sum of the potential energy and kinetic energy of the load being lifted [26].

8. A symmetrical lifting is assumed to be "ideal" lifting. This means that the angle of symmetry is zero. The angle of symmetry is defined as the angle formed by twisting the body from the neutral body position.

9. The spine with the trunk muscles and other soft tissues are regarded as the weight-bearing unit [27].

The anthropometric dimensions introduced into the model and regarded as variables are: height shrinkage (x), the value of length of the spine from the first thoracic to the last lumbar vertebrae of the trunk (L), chest breadth (l_f) and chest depth (l_s).

The parameters used in the model are young modulus of elasticity of the articular cartilage (E), velocity of lift (u), acceleration due to gravity (g), vertical location of the load (V), horizontal length of the load from the ankles (H), vertical displacement of the load (D), the lift angle (θ)(see Figure 2).

Between the last cervical vertebrae and the last lumbar vertebrae, there exist 17 discs and thus endplates. Each of these behaves as a spring represented in Figure 1.

Assuming a non-linear spring for each of the discs, the strain energy is given by

$$U_i = \int_0^{\delta_i} F_i d\delta_i \quad (1)$$

Also, the force-deflection law is given as

$$F_i = k_i \delta_i \quad (2)$$

Combining (1) and (2), we have

$$U_i = \int_0^{\delta_i} k_i \delta_i d\delta_i \tag{3}$$

Integrating (3) gives

$$U_i = \frac{k_i \delta_i^2}{2} \tag{4}$$

From expression (2) $k_i = \frac{F_i}{\delta_i}$

$$\therefore U_i = \frac{F_i \delta_i}{2}$$

The sum of all strain energies that shall be the strain energy at the back is given as

$$U = \sum_{i=1}^{17} U_i = \sum_{i=1}^{17} \frac{F_i \delta_i}{2} \tag{5}$$

But $F_i = F_1 = F_2 .... = F_{17} = F$ since the discs are connected in series, the force compressing them is the same [24].
Also, the total shrinkage on all the discs, x, is given by the following expression:

Since the sum of individual disc shrinkage should be the overall spinal shrinkage,

$$x = \delta_1 + \delta_2 + \delta_3 + \ldots\ldots\ldots\ldots.. \delta_{17} \tag{6}$$

Therefore, the strain energy at the spine may be expressed as follows:

$$U = \frac{Fx}{2} \tag{7}$$

where *F= The spine load*

x= spinal shrinkage

Strain Energy, $SE = ½Fx$ [28] (8)

Kinetic Energy, $KE = ½ mu^2$ (9)

Potential Energy, $PE = mg (D+V)$ (10)

Where D = Vertical displacement of the load, m

V = Vertical location of the load, m

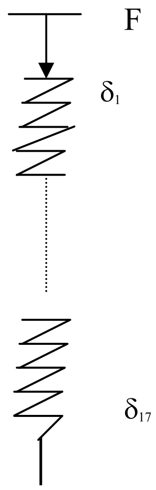

Figure 1. The Vertebrae behaving as a spring

The spring constant, k, is given by:

k=F/x=AE/L [24] (11)

Combining equations (8) and (11) we have

$$SE = \frac{AEx^2}{2L} \tag{12}$$

During lifting, the angle between the hip and the thigh (θ, the lift angle) (Figure 2) plays a prominent role to give the load or strain along the spinal column. Resolving the force or weight of the load along the spinal column gives the potential energy (PE) as:

$$PE = \text{Mg } (D+V)/\sin\theta \tag{13}$$

$$\text{Tan } \theta = (D+ V)/H \tag{14}$$

From energy conservation principle

$$SE = PE + SE \tag{15}$$

The strain energy due to lifting and that due to the upper body (i.e. head, trunk and arms) weight must be equal to the sum of strain energy due to upper body weight only and that is due to the lift weight.

Therefore,

$$SE_T = SE_b + SE_l \tag{16}$$

where

SE_T = Strain energy due to the upper body weight and lift weight

SE_b = Strain energy due to the upper body weight

SE_l = Strain energy due to the lift weight

However, strain energy is the sum of potential and kinetic energies,

Hence,

$$SE_T = PE_T + KE_T \quad (17)$$

From equations 2 and 3

$$KE_T = M_T u^2/2 \quad (18)$$

$$E_T = M_T g\,(D+V)/\sin\theta \quad (19)$$

Where

$M_T = M_o + M_b$

M_o = the load weight

M_b = the upper body weight

$$SE_T = M_T g\,(D+V)/\sin\theta + M_T u^2/2 \quad (20)$$

Similarly,

$$SE_b = M_b g(D+V)/\sin\theta + M_b u^2/2 \quad (21)$$

But,

$$SE_l = SE_T - SE_b \quad (22)$$

Therefore,

$SE_l = (M_o + M_b)\, g\,(D + V)/\sin\theta + (M_o + M_b)u^2/2 - [M_b g\,(D + V)/\sin\theta + M_b u^2/2]$

$= M_o g\,(D + V)/\sin\theta + M_b g\,(D + V)/\sin\theta + M\,u^2/2 + M_b u^2/2 - M_b g\,(D+V)/\sin\theta - M_b u^2/2$

$$= M_o g\,(D + V)/\sin\theta + M\,u^2/2 \quad (23)$$

Hence, combining this with equation (5), then:

$$AEx^2/2L = M_o g\,(D+V)/\sin\theta + 1/2 M_o u^2 \quad (24)$$

Recall that the Young Modulus of Elasticity, E in the model is thus obtained within the elastic deformation region. It may therefore be argued that the load to be lifted as long as it is obtained using this E should be safe for the human subject. A safe lift weight (SWL) may therefore be defined as that weight whose axial compressive force component perpendicular to the disc plane is incapable of causing plastic deformation of the disc.

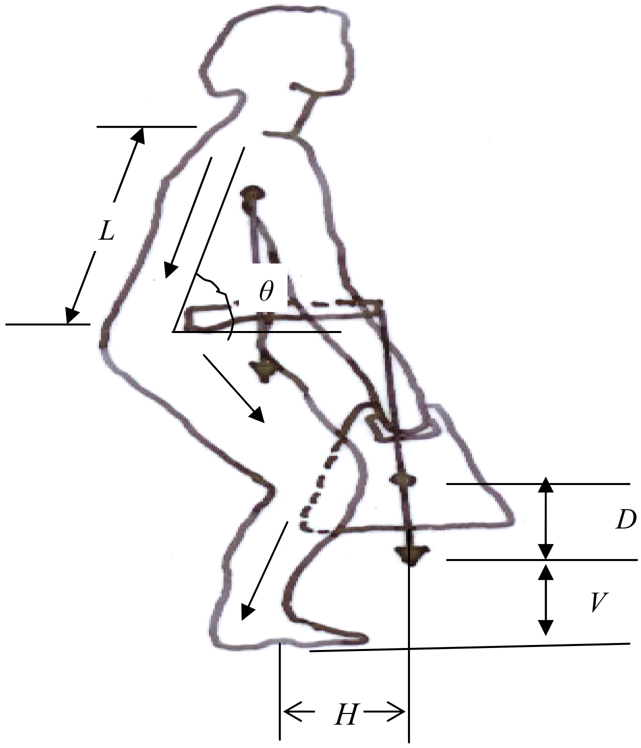

Figure 2. Lifting Body Structure: H, horizontal location of load; V, vertical location; D, Vertical displacement of load

Making m the subject of the equation;

$$M_o = \frac{\pi l_f l_s x^2}{4L} \left(\frac{E\left\{\frac{D+V}{H}\right\} Cos\theta}{2gD + u^2 \left\{\frac{D+V}{H}\right\} Cos\theta} \right) \quad (25)$$

From the foregoing, the m derived in equation (25) may be regarded as the Safe Weight of Lift (SWL).

$$SWL = M_o \quad (26)$$

2.2 Model Application

In order to apply the model, a range of values of the task parameters: *D* (vertical displacement), *V* (vertical location of the load), *H* (horizontal location of the load) have been adopted from [29]; E from [25] and u from [22].

Measurements of L (from the first thoracic to the last lumbar), l_f (chest breadth) and l_s (chest depth) have been taken from eighty four (84) workers comprising those in the factory and market labourers engaged in lifting tasks that have a duration of eight hours. Also, the heights of each worker were measured just before the commencement of work (in the morning) and after the conferment of work (in the evening) to determine the post-work spinal shrinkage. The age range of the workers was from 18 to 57 years.

The obtained values using expression (26) have been statistically compared to the values of RWL (one lift per minute) and MAWL using Paired-Samples T- Test at 95 % confidence level.

3. RESULTS AND DISCUSSION

The summary of the obtained data is presented in Table 1.

It is worth noting, that the MAWL values are those established by [8].

At 95 % confidence level, the SWL values determined with L = 0,6 m, x = 0,014 m and A = 0,046 m^2 are significantly different from the corresponding values of RWL (p = 0,000) and those of MAWL (p = 0,000). [30] The maximum permissible spinal shrinkage of 0,021 m was obtained. Consequently, this entailed that to reduce low back problems, the limit should not be exceeded. The SWL_{Max} values have been thus obtained with x = 0,021 m, L = 0,6 m and A = 0,046 m^2 and are accordingly significantly different from the corresponding values of RWL (p = 0,000) and those of MAWL (p = 0,000). This presupposes that the SWL and SWL_{Max} values may be more protective of the workers than both the RWL and MAWL values. Table 2 shows the values of RWL, MAWL, SWL and $SWL_{Max,}$

Table 1. Summary of Data

	Age/ Years	Height (Morning)/ m	Height (Morning)/ m	Chest Depth/ m	Chest Breadth/ m	Length of Vertebral Column/m	Spinal Shrinkage/ m	Chest Area/ m^2
Mean	36,6	1,69	1,68	0,19	0,25	0,52	0,014	0,038
Maximum	57	1,8	1,78	0,26	0,28	0,7	0,025	0,053
Minimum	18	1,56	1,56	0,16	0,22	0,44	0,000	0,029
5^{th} %ile	23,2	1,61	1,59	0,17	0,23	0,46	0,000	0,032
50^{th} %ile	38	1,69	1,68	0,19	0,26	0,52	0,013	0,038
95^{th} %ile	50	1,77	1,76	0,23	0,28	0,6	0,025	0,046

The model seems to confirm the work of [31] that the co-efficient of proportionality between load and spinal shrinkage is inversely proportional to the cross-sectional area of the lumbar discs. The model illustrates that there exists an association between body height and lifting task as noted by [32]. Furthermore, it goes further to confirm the notion by [14] that the ability to carry load steadily declines with increase in height of people. This may further explain why weight lifters are usually short and build the muscles at the trunk. Another interesting factor about the model is the fact that the weight of the lifter is not represented in the model, signifying that body’s weight may not be a factor that may determine the load to be lifted.

Table 2. Comparison between RWL, MAWL, SWL and SWL_{Max} values

D (m)	V (m)	H (m)	RWL (Kg)	MAWL (Kg)	SWL_{Max} (Kg)	SWL (Kg)
0,25	0,260	0,37	9,9	11,0	6,6	2,4
0,25	0,260	0,45	8,2	9,0	6,1	2,2
0,25	0,260	0,58	6,3	9,0	5,6	2,0
0,51	0,125	0,37	8,6	11,0	5,6	2,1
0,51	0,125	0,45	7,1	9,0	5,3	1,9
0,51	0,125	0,58	5,5	8,0	4,8	1,8
0,76	0,000	0,42	7,0	9,0	4,8	1,7
0,76	0,000	0,5	5,9	8,0	4,5	1,7
0,76	0,000	0,63	4,7	7,0	4,2	1,5
0,25	0,920	0,37	11,1	12,0	3,4	1,2
0,25	0,920	0,45	9,1	10,0	3,3	1,2
0,25	0,920	0,58	7,1	10,0	3,2	1,2
0,51	0,785	0,37	10,5	10,0	3,1	1,1
0,51	0,785	0,45	8,6	9,0	3,0	1,1
0,51	0,785	0,58	6,7	9,0	2,9	1,1
0,76	0,660	0,37	10,0	9,0	2,8	1,0
0,76	0,660	0,45	8,2	9,0	2,8	1,0
0,76	0,660	0,58	6,4	9,0	2,7	1,0
0,25	1,540	0,37	8,9	10,0	2,3	1,0
0,25	1,540	0,45	7,3	8,0	2,2	1,0
0,25	1,540	0,58	5,7	8,0	2,2	1,0
0,51	1,410	0,37	8,5	9,0	2,1	1,0
0,51	1,410	0,45	7,0	7,0	2,1	1,0
0,51	1,410	0,58	5,4	7,0	2,1	1,0
0,76	1,280	0,37	8,6	8,0	2,0	1,0
0,76	1,280	0,45	7,1	7,0	2,0	1,0
0,76	1,280	0,58	5,5	6,0	2,0	1,0

The parameters of the model are based on the measurements taken from *in vivo* subjects rather than *in vitro* subjects except the Young Modulus of Elasticity of the articular cartilage which is a constant. The model is a dynamic one, having taken the minimum peak velocity of lift into consideration. Since the human tissue is visco elastic, [34] has suggested that prolonged loads may result in residual deformation and repeated loads may reduce their tolerances.

However, since the model employs the difference between the height of the human subjects in the evening and in the morning respectively, the Young Modulus of Elasticity of the weakest point may be reduced drastically, because it is believed that mechanical damage to the human subjects is due to either prolonged or repeated loading..

The model is also subject-specific as required parameters can be taken few minutes apart from spinal shrinkage and inserted into the model to obtain the Safe Weight of Lift for the subject in question. This is important as (spine) loading is related to individual capability [35] and this capability is dependent on anthropometric dimensions.

From the foregoing, the model seems relevant in the determination of a load to be lifted manually and safely by the human subjects. Hence, the mathematical model incorporating the lifters' anthropometric dimensions for predicting SWL appeared to be realistic.

4. CONCLUSION

The study proposed a mathematical model to calculate the Safe Weight of Lift for manual load lifting. The model not only incorporates the lifting task parameters as used by NIOSH but also some relevant lifter's anthropometric dimensions (the chest area and spine length), spinal shrinkage and lift velocity. The model to measure the safe lifting capacity of an individual has been shown to be valid.

REFERENCES

[1] Ismaila, S.O.: *Post-Work Height Shrinkage Based Model for Predicting Safe Weight of Lift*. Unpublished PhD Disseration, Department of Industrial and Production Engineering, University of Ibadan, Ibadan, Nigeria, 2006.

[2] Health and Safety Commission: *Manual Handling Guidance Regulations,* HMSO, London, 1993.

[3] Murphy, P.L., Sorock, G.S., Courtney. T.K., Webster, B.S. and Leamon, T.B.C.: *Injury and Illness in the American Workplace: A comparison of data sources*. American Journal of Industrial Medicine, 30 (1996), 130 – 141.

[4] Dempsey, P.G., Hasheni, L. C.: *Analysis of workers compensation claims associated with Manual Material Handling,* Ergonomics, Vol. 42 (1999), 1, p. 183 – 195.

[5] ILO (International Labour Office): *Maximum Permissible Weight to be Carried by One Worker.* Geneva, 1964.

[6] Snook, S.H.: *Psychophysical considerations In permissible loads*. Ergonomics, Vol. 28 (1985[a]), p. 327-330.

[7] Snook, S.H.: *Psychophysical acceptability as*

a constraint in Manual working capacity, Ergonomics, 28 (1985b), p.331-335.

[8] Snook, S.H., Ciriello, V. M.: *The design of manual handling tasks: revised tables of maximum acceptable weights and forces*, Ergonomics, 34 (1991), p. 1197-1213.

[9] Ciriello, V. M., Snook S.H., Blick A.C., Wilkinson P.L.: *The effects of task duration on psychophysically determined maximum acceptable weights and forces*, Ergonomics 33 (1990), p. 197-200.

[10] Nussbaum, M. A., Lang A.: *Relationships Between static load acceptability ratings of perceived exertion and biomechanical demands*. International Journal of Industrial Ergonomics 35 (2005), No. 6, p. 547 –557.

[11] Dempsey, P.G., Ayoub, M. M.: *The Psychophysical Approach to Manual Materials Handling task design,* Ergonomics 42 (1999), No 1, p. 17-31.

[12] Garg, A.: *A metabolic prediction model for Manual Materials Handling Jobs.* PhD Dissertation Ann Arbor: University of Michigan, 1976.

[13] Samanta, A., Chartterjee, B.B.: *A Physiological study of Manual Lifting of Loads in Indians.* Ergonomics 24 (1981), *No* 7, p. 557 – 664.

[14] Chaffin, D.B., Anderson G.B.J.: *Occupational Biomechanics*. John Wiley and Sons. New York (2nded),1991.

[15] Dieen, V. J.H., Hoozemans, J.M. M., Toussaint, M.H.: *Stoop or Squat: a review of biomechanical studies on lifting technique*,Clinical Biomechanics 10(1999), p.685- 696.

[16] Waters, T.R., Putz-Anderson, V., Garg A., Fine L.J.: *Revised NIOSH equation for the design and evaluation of Manual lifting tasks.* Ergonomics*,* 36(1993), p. 749. – 776.

[17] Nussbaum, M. A., Chaffin D. B., Baker G.: *Biomechanical analysis of materials handling manipulators in short distance strength, spine forces and muscular antagonism,* Ergonomics 42 (1999), 12, p. 1597.-1618.

[18] Mc Gill, S.M. : *The biomechanics of low back injury: implications on current practise in industry and the clinic*, Journal of Biomechanics, Vol. 30 (1997), p. 465-475.

[19] Cenar, Y.: *Mechanical Characterization of a Simple Gel in a Prototype Device that models a Degenerative Intervetebral Disc*, Msc Thesis of Oregon State University, United States, 2007.

[20] Joshi A.B.: *Mechanical Behaviour of the Human Lumbar Inter vertebral disc with Polymeric Hydrogel Nucleus Implant: An Experimental and Finite Element Study*. An Unpublished Dissertation Submitted to Drexel University, 2004.

[21] Potvin, J.R.: *Use of NIOSH equation inputs to calculate lumbosacral compression forces,* Ergonomics, Vol. 40 (1997), No 7, p. 691. – 707.

[22] Lin, C.J., Bernard, T.M., Ayoub, M.M.: *A biomechanical evaluation of lifting Speed using work and moment related measures,* Ergonomics*,* Vol. 42 (1999), No 8, p. 1051.-1059.

[23] Glickman, J.,: The NASI Report: *Toward a Resolution of the Bigfoot Phenomenon* from http:/www.bigfootencounters.com/biology/nasi.htm. Accessed on 6/2/09, 1998.

[24] Marshek, M. K.: *Design of Machine and structural parts*, John Wiley and Sons Inc. New York, 1987.

[25] Sokoloff, L.: Elasticity of Ageing Cartilage, *Fed. Proc. Fed AM socs exp Biol.* 25, 1966, pp. 1089- 1095.

[26] Leskinen, T.P.J., Stalhammer, H.R., Kuorinka, I.A.A., Troup, J.D.G.: *The effect of inertial factors on spinal stress when lifting*, Engineering in Medicine, 12 (1983), p. 87–89.

[27] Bridger, R.S.: *Introduction to Ergonomics*, McGraw Hill, Inc. New York, 1995.

[28] Ryder G.H., *Strength of materials,* Macmillan Publishers Ltd. London. Safety and Health, Cincinnati, OH. 1969.

[29] NIOSH, *Work Practices Guide for Manual Lifting,* NIOSH Technical Report No 81 – 122, US Department of Health and Human Services, National Institute for Occupational. 1981

[30] Ismaila, S.O., Charles-Owaba, O.E.: Determination of The Highest Permissible Spinal Shrinkage, Australian Journal of Basic and Applied Sciences*,* 2 (2008), 4, p. 872. – 875, 2008.

[31] Althoff, I., Brinckmann, P., Frobin, W., Sandover, J., Burton, K..: *An Improved method of Stature measurement for quantitative determination of Spinal loading: Application to sitting postures and*

whole body vibration, Spine, Vol. 17 (1992), 6, p. 682.-693.

[32] Schenk, P., Klipstein, A., Spillmann, S., Stroyer, J., Laubli, T.: *The role of back muscle endurance, maximum force, balance and trunk rotation control regarding lifting capacity*. European Journal of Applied Physiology, 96 (2006), 2, p.

[33] Tyrell, A.R., Reilly, T., Troup, J.D.: *Circadian variation in stature and the effects of spinal loading,* Spine, Vol. 10 (1985), No 2, p.161-164.

[34] Kumar S.: *Cumulative load as a risk factor for back pain.* Spine, 15 (1990), p. 1311-1316.

[35] Reilly Thomas and Freeman Kirsten A.: Effects of loading on spinal shrinkage in males of different age groups *Applied Ergonomics* Vol 37 (2006) Issue 3, p. 305 – 310

Received: 11. 04. 2011.

Accepted: 30. 10. 2011.

Authors' address

Salami O. Ismaila
Department of Mechanical Engineering,
University of Agriculture,
P.M.B 2240,
Abeokuta, Ogun State, Nigeria
Oliver E. Charles-Owaba
Department of Industrial and Production Engineering,
University of Ibadan,
Ibadan, Oyo State, Nigeria.
e-mail addresses of the authors:
ismailasalami@yahoo.com
oeowaba@yahoo.com