Modelling to Determine Fit between Work Tasks and the Bending Capabilities of Subjects

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Abstract. The limiting extent to which subjects can bend over while carrying out repetitive task, as measured by the postural angle, θ, in degree in relation to work space, without developing lower back pain (LBP) that is caused by over exertion of the thora-columbar force has been ascertained with the aid of anatomical model developed in this study. A free body diagram (FBD) of the human anatomical system was developed and used to carry out a biokinetic analysis in order to determine the theoretical relationship between the force erector muscle and the anthropometric variables. The model was fitted into anthropometric data of Nigeria population presented in percentile values. Our results suggest that the magnitude of erector muscle force is to a large extent determined by the body weight (WB) and trunk angle, θ. And that the reaction forces generated at the hip can be of the order of ten raised to power 3 of the body weight (WB). The utility of the research outcome appears appealing especially to Industrial Engineers who may find it needful for work space and jobs design.

Introduction

Lower back pain (LBP) is a physiological condition that has been largely attributed to some risk factors such as bending and twisting (awkward posture) which subjects encounter in the industry, household, and agricultural related tasks especially in third world countries with special reference to Africa, and Nigeria in particular. Although back injuries account for no work-related deaths, they do account for a significant amount of human suffering, loss of productivity, and economic burden on compensation systems. Back disorders are one of the leading causes of disability for people in their working years and afflict over 600,000 employees each year with a cost of about US$50 billion annually in 1991 according to US National Institute for Occupational Safety and Health (NIOSH) [1]. Agricultural practice in Nigeria is done at subsistence level and it is labour intensive because of the prevalent low level of industrialisation in the sector. Past studies had adopted descriptive approaches that appear to lack supportive data and rigorous quantitative analysis, which this current study furnishes [2].

Spectacularly, the anthropometric data used in this study is a preliminary anthropometric survey of Nigerian Population carried out by the lead author.

Most studies in Nigeria relevant to the subject area could not contextualise modeling of LBP because of dearth of relevant anthropometric data. The current study has been able to establish the relationship between standing height and the following:

(i.) shoulder to buttock distance;
(ii.) below shoulder to buttock distance respectively for the Nigerian population.

Moreover, the study found out that as subjects which are subjected to bending tasks adopt postures with a postural angle greater than 80^0, the force erector muscle caused by bending and responsible for LBP tends to varnish.
A survey study of random samples of workers in Gazel, France was carried out using multivariate analysis in order to ascertain the relationship between LBP and durations of exposure to the biomechanical strains. It was found out that the odd ratio for twenty years of exposure to driving and bending/twisting for men is 1.24 and 1.37 respectively. The study concluded that repetitive bending tasks have a long-term effect on subjects [3].
There had been considerable interest in the study of relationship between bending and LBP. Representative works in this area include the following [4, 5, 6, 7, 8].
The main object of this study is to develop a model that explains the relationship between thora-columbar muscle force and some ergonomic variables. The model will be useful for educating people on the best posture in order to reduce the stresses and strains imposed on the thora-columbar muscle, which are major sources of lower and upper spine disorders.

Methodology

This study is an analytical and applied research aimed at developing and testing a model that explains the relationship between human bending capacity and the anthropometric variables. The model developed was fitted into anthropometric data obtained from previous studies by the lead author. The anthropometric data inputted comprised anthropometric measurements of male and female students of University of Benin, Benin City, Nigeria (unpublished), and another one dealing with anthropometric measurements of Nigerian adult working class. These data exist in percentile measures. It is well known that anthropometric data vary significantly from country to country and race to race [9]. However, the anthropometric measures obtained from the studies under reference are specific to Nigerian race but representative of Africa which is made up of developing nations. Arising from this premise, the data can be generalised for developing nations. From the data, the standing height, shoulder-to-buttock, below-shoulder-to-buttock distances, and body weight were obtained. The anthropometric variables such as the postural angle, θ, and angle of erector muscle with respect to trunk, α, were simulated.
The average person concept of human factors engineering is assumed by which we mean that the body parts dimensions are proportional to the height and weight respectively. Our results were compared with values in the literature.

Modelling Bending. Fig. 1 depicts a subject adopting a bending posture. The associated Free Body Diagram (FBD) is shown in Fig. 2. The average person concept is assumed for the purpose of this modelling.

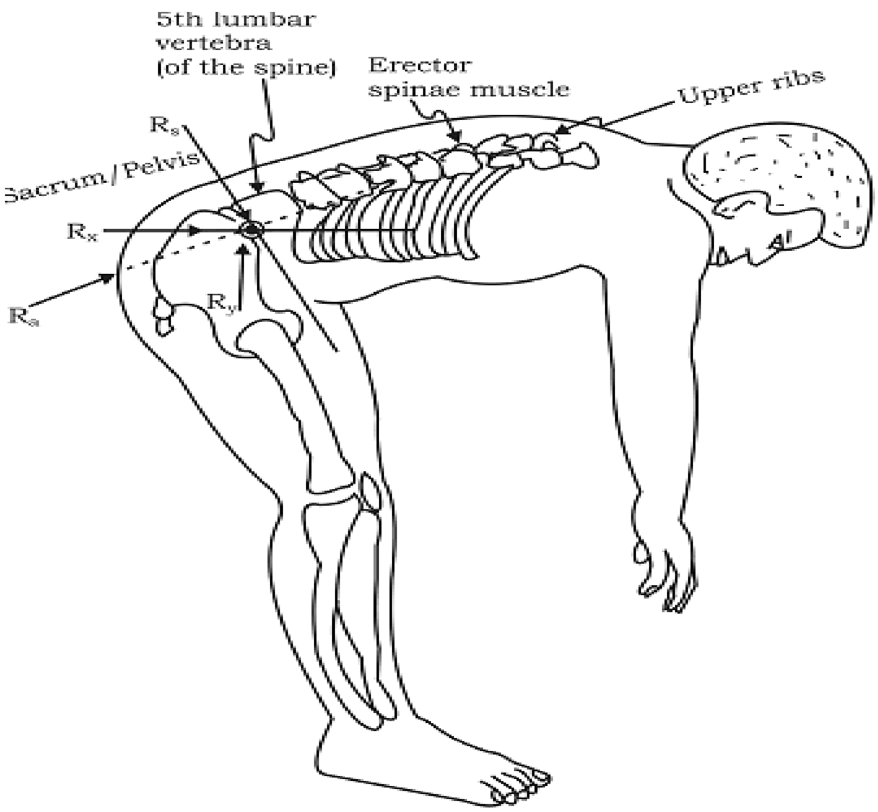


Fig. 1: Approximate Anatomical Model of Subject Bending Over

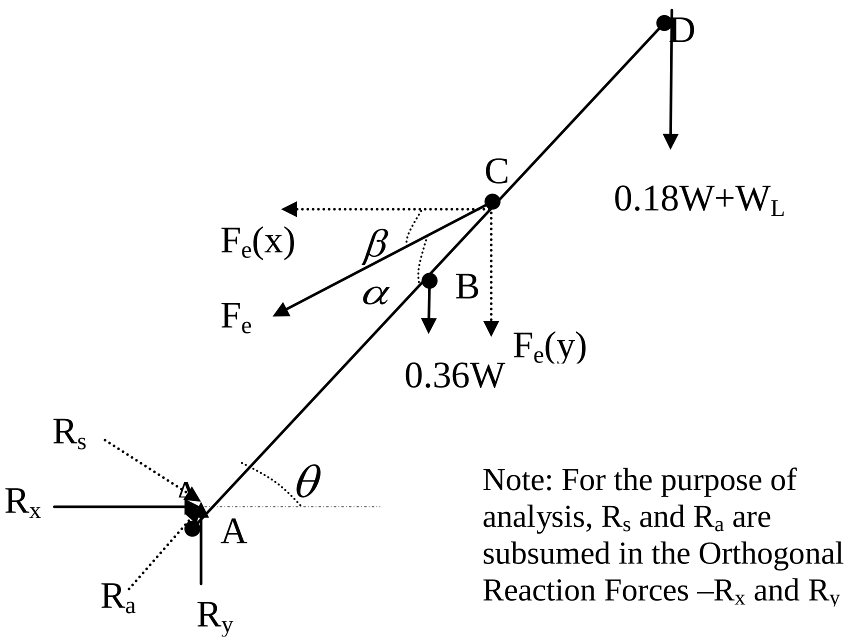


Figure 2: Free Body Diagram (FBD) of Subject Subjected to Bending Over-task

Two basic body parameters namely: height at erect position (H) in metres and body weight (W) in Newton are considered. The various body parts dimension and weight are assumed to be respectively proportional to the height and weight of the subject. The constants of proportionality are depicted in Table 1.

Table 1: Anthropometric Modelling Data

Body Segment	Segment Length (Fraction of height, H)	Segment Weight (Fraction of weight,W)
Head and neck	0.17	0.08
Forearm and hand	0.20	0.20
Upper arm	0.20	0.03
Arm	0.40	0.05
Head, neck and both arms	-	0.18
Thorax and abdomen	0.30	0.36
Pelvis	-	0.16
Foot and foreleg	0.29	0.05
Upper leg	0.24	0.10
Leg	0.53	0.15
Head, neck, both arms, thorax, abdomen, and three-eights pelvis	-	0.60
One leg and five-eighths pelvis	-	0.25

Source: [10]

The anthropometric survey, depicted in Tables 2 and 3 establish the following relationships. Midpoint of spine measured from pelvic girdle (AB) equals half the ratio of “shoulder to buttock” distance to that of “standing height” which is 0.15H. The distance of the point of attachment of erector muscle tensor to the spine from the pelvic girdle (AC) equal to the ratio of “below shoulder to buttock” distance to that of standing height which is 0.20H. While the distance from the end point of the thora-columbar spine to the pelvic girdle (AD) equal to the ratio of “shoulder to buttock” distance to that of standing height which is 0.30H.

Table 2: Anthropometric Data of Male and Female Undergraduate Students of the University of Benin, Benin City, Nigeria.

Percentile	Weight (kg)		Height (m)		Shoulder To Buttock (m)		Below Shoulder to Buttock (m)	
	Male	Female	Male	Female	Male	Female	Male	Female
5th	55	52	1.62	1.55	0.49	0.50	0.33	0.33
25th	62	59	1.70	1.59	0.53	0.52	0.35	0.34
50th	68	62	1.75	1.64	0.55	0.54	0.36	0.36
75th	74	69	1.80	1.69	0.58	0.56	0.32	0.37
95th	86	81	1.90	1.75	0.63	0.60	0.42	0.40

Table 3: Anthropometric Data of Nigeria Male and Female Adult Working Class

Percentile	Weight (kg)		Height (m)		Shoulder To Buttock (m)		Below Shoulder to Buttock (m)	
	Male	Female	Male	Female	Male	Female	Male	Female
5th	47.00	45.00	1.49	1.51	0.47	0.29	0.31	0.29
50th	64.00	58.00	1.72	1.63	0.56	0.35	0.37	0.35
95th	85.40	92.60	1.88	1.83	0.66	0.41	0.44	0.41

Reference to Fig. 1 and Fig. 2,

$$\theta = \alpha + \beta$$

$$F_e(x) = F_e.\cos\beta$$

$$F_e(y) = F_e.\sin\beta$$

$$\sum F_{x,y} = 0, \rightarrow + \uparrow^{+}$$

$$\Rightarrow R_x - F_e.\cos\beta = 0 \quad (1)$$

$$\Rightarrow R_y = F_e \sin\beta + 0.54 W_B \quad (2)$$

Take moments about A: $\sum M_A \circlearrowleft^{+} = 0$

$$-F_e(x).(AC\sin\theta) + F_e(y).(AC.\cos\theta) + 0.36W.(AB\cos\theta) + 0.18W_B(AD\cos\theta) = 0$$

Substituting the values of AB, AC and AD in terms of H and the corresponding values of $F_e(x)$, $F_e(y)$, we obtain

$$F_e[\sin\theta\cos\beta - \cos\theta\sin\beta] = 0.54 W_B \cos\theta.$$

Hence,

$$F_e = \frac{0.54 W_B \cos\theta}{\sin(\theta - \beta)} = \frac{0.54 W_B \cos\theta}{\sin\alpha} \quad (3)$$

Fig. 3 shows the vector diagram obtained from the FBD in Fig. 2 used for the computation of axial reaction force along the central axis of the spine.

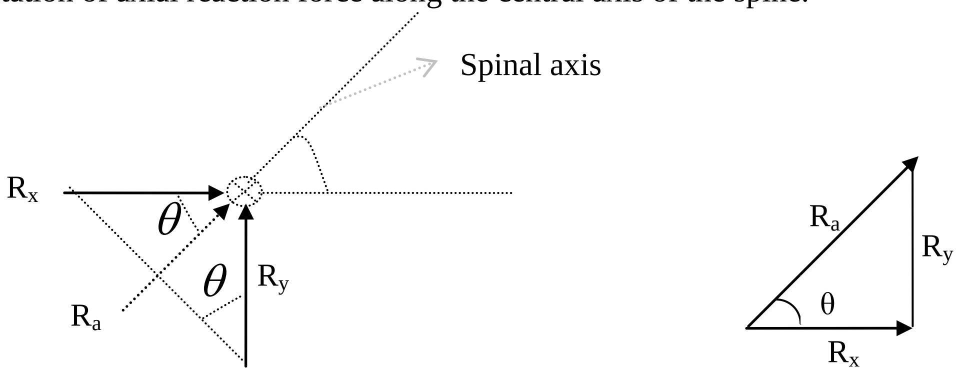
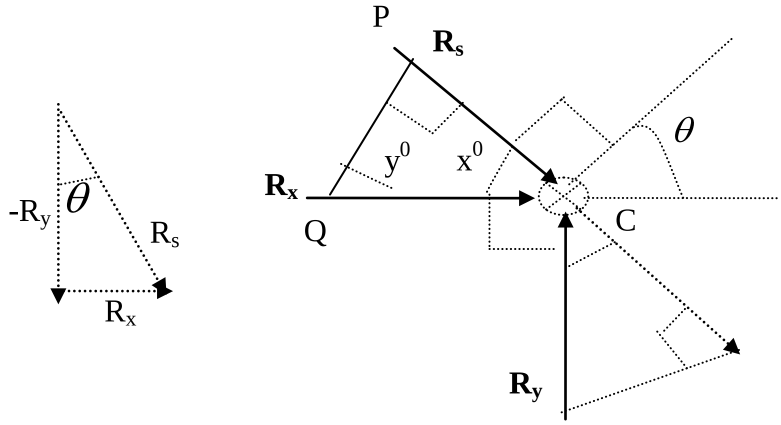


Fig. 3: Vector Diagrams for the Computation of Axial Reaction Force Along the Central Axis of Spine

$$\Rightarrow R_a = R_x \cos\theta = R_y \sin\theta \quad (4)$$

Fig. 4 shows the vector diagram obtained from the FBD in Fig. 2 used for the computation of shear reaction stress perpendicular to the axis of spine.



$x^0 + 90 + \theta = 180^0$

$x^0 = 90 - \theta$

And for ΔPQC :

$y^0 + x^0 + 90 = 180^0$

$\Rightarrow y^0 = 90 - x^0$

$= 90 - (90 - \theta)$

$= \theta$

Fig. 4: Vector Diagrams Trigonometric Expression for the Computation of Shear Reaction Stress Perpendicular to the Axis of Spine

And by scalar resolution:

$$\Rightarrow R_s = R_x \sin\theta = -R_y \cos\theta \qquad (5)$$

Results

Incorporating Anthropometric Data to the Model Developed. Table 4 shows the computation of the erector muscle force, F_e, shear reaction stress perpendicular to the axis of spine, R_s, and the axial reaction force along the central axis of the spine, R_a, for the male working class in Nigeria using the simulated values of the anthropometric variables.

Table 4: Computation of the Erector Muscle Force, F_e, Axial Reaction Force, R_a, and Shear Reaction Force, R_s for Nigeria Male Working Class.

Percentile	Weight (N)	Anthropometric Variables			F_e (N)	F_e/W	R_x	R_y (N)	R_a (N)	R_s (N)
		α	β	θ						
		1	5	6	14099	30	14045.02	507.5746	14043.61	1467.704
		5	25	30	2526	5	2289.614	219.7908	1982.806	1144.807
		10	50	60	729	2	468.8007	126.9	234.4003	405.9814
		15	75	90	0	0	0	0	0	0
5	470	20	100	120	-371	-1	64.45184	-126.9	-32.2259	55.8153
		1	5	6	19198	30	19125.13	691.1654	19123.21	1998.576
		5	25	30	3440	5	3117.772	299.2896	2699.991	1558.886
		10	50	60	993	2	638.3669	172.8	319.1834	552.8257
		15	75	90	0	0	0	0	0	0
50	640	20	100	120	-505	-1	87.76421	-172.8	-43.8821	76.00381
		1	5	6	25617	30	25520.09	922.2739	25517.54	2666.85
		5	25	30	4590	5	4160.277	399.3646	3602.8	2080.139
		10	50	60	1325	2	851.8208	230.58	425.9104	737.6768
		15	75	90	0	0	0	0	0	0
95	854	20	100	120	-674	-1	117.1104	-230.58	-58.5552	101.4176

It is evident that the less generous the postural angle, θ (trunk angle); the higher the force-body weight ratio and at extreme postural angle a limiting force-body weight ratio is attained, giving a force/weight space of (-1, 30). It is further evident from the table that at awkward postures, the axial thrust rises to 25, 19 and 14 kN for 95^{th}, 50^{th} and 5^{th} percentiles respectively.

Discussion

Arising from the results of this study, it is evident that the relationship between erector muscle force, F_e (generated by bending over) and postural angle, θ, has been established. Moreover, the relationship between body weight, postural angle, axial reaction force at the hip, shear reaction force at the hip, as well as vertical and orthogonal hip reaction forces have been equally obtained for different percentiles of Nigeria population.

Our results show that at awkward postural angles, the forces involved are of tremendous magnitude, of the order of ten raised to power three of the body weight. Literature results have reported force/weight ratio (F_e/W_B) of the order of 10^6 [4].

Figure 5 dealing with force and postural angle plot shows that the smaller the postural angle, θ, (substantial bending over) the erector muscle force increases in a exponential order.

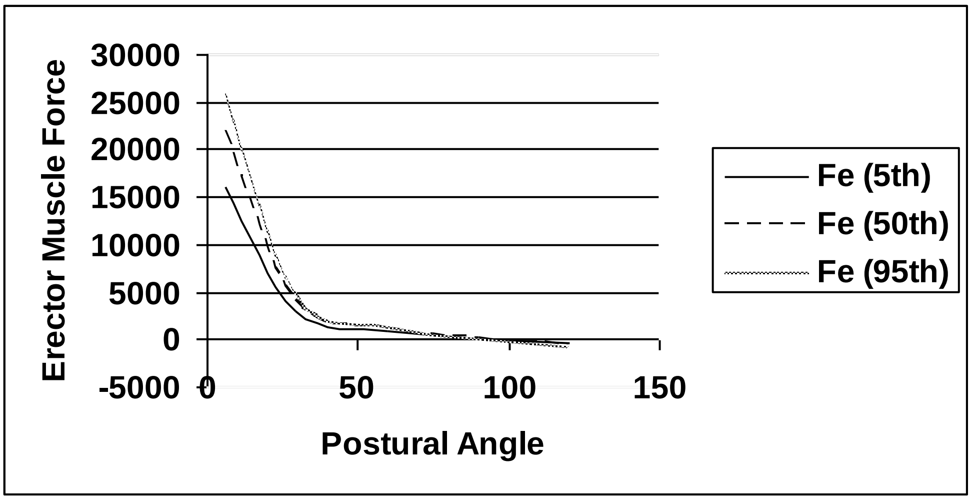


Fig. 5: Erector Muscle Force and the Postural Angle Plot

And this phenomenon explains the dynamics of pulling heavy trucks and tankers in the world's-strongest-man championship. Usually the amount of force required is way above the weight of the strong-man.

Perhaps it is pertinent to note that in most developing countries, particularly Nigeria where this study was carried out, there is low level of mechanization of agricultural practice and materials handling, and the limitation has compelled agricultural and industrial workers to resort to manual tasks that involve repetitive awkward posture. Some examples of manual tasks involving repetitive awkward bending include tilling of soil for planting crops, harvesting, bush clearing, weeding and tailoring. In the area of domestic chores, economic condition and limited education limit the degree to which workspace designs are properly carried out. In this regard, most household chores are done in such a way that most humans are made to fit the workspace, a kind of procrustean ergonomics. In the industry, for similar reasons a lot of manual tasks involving repetitive bending over are still being carried out which oftentimes lead to development of LBP.

Perhaps the selling point of this research study is that the models developed can guide human factor engineers in the design of workspace and jobs where repetitive bending is involved. The model defines limit of human capabilities vis-à-vis postural angle and body weight. In this way possible hazards and risks associated with doing specific repetitive tasks involving awkward and sustained bending can be identified and controlled in order to reduce or possibly eliminate the concomitant epidemiological problems.

Conclusion

A model explaining the relationships among postural angle, thora columbar force, hip orthogonal reaction forces, axial reaction force and shear reaction force for the hip have been developed.

The model has appealing utility in the sense that it can be used for determining the safe bending posture for workers carrying out repetitive bending tasks. It is also a useful guide for industrial engineers carrying out workspace design.

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