DYNAMICAL PRINCIPLE OF LIFTING ACTION

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The manual lifting is a prevalent action during daily life and professional work. So low-back pain is common among these human. Many experts make researches on this subject in various fields with experimental method. In this paper our research and analysis based on classical dynamic method. We simulated the lifting movement in the dynamic multi-segment model and defined θ (the angle between leg and ground) as generalized coordinate. Hence the equations of multi-body system were established. Through solving these equations, the angular velocity and angular accelerate of hip angle $\dot{\beta}$, $\ddot{\beta}$ and internal forces and moment of hip N_X, N_y, M were obtained. Especially, analytical solution of $\dot{\theta}$, was be obtained, it is convenient to further research internal mechanics of lifting 。Based on above analysis, the conclusions show that main influence of N_X, N_y , M is the change of angular acceleration $\ddot{\theta}$. The key factor to avoid injure is control the type of smooth lifting.

KEY WORDS: dynamic model, lifting, multi-segment

INTRODUCTION: The lifting is an action during daily life, especially to some professional worker. The action often makes injury at low back pain of them. A lot of researchers pay great attention to the relationship between human healths and injury of professional worker. Some experts of foreign countries, research on this subject in the filed of medicine, physiology, psychophysics and biomechanics. Most biomechanical researchers of our country concentrate on technical analysis for athletics. The subjects of research related to the human health are rather rare. Especially, there are a few articles about dynamic analysis on ergonomic. In this paper we will analysis mechanical principle of lifting action by using the method of classical dynamic and multi-body model. Muscular mechanical energy expenditure in manual materials handing and dynamic factors during asymmetrical lifting were be researched (Gagnon 1991, 1992, 1996) Dolan (Dolan et. al,1994) researched bending and compressive stresses acting on the lumbar spine during lifting. The method of their researches is main experimental measuring combined with statistics and numerical computing to make some suggestions for practical problems. In China some scholar (Lei Ling 2001, Zhu Liping 1999) did analysis and research on ergonomic and biomechanics of lifting respectively.

DYNAMIC MODEL AND CALCULATIONS: The injury at low-back often happens during lifting. It is corresponding conclusion among these researchers. But they hold different analysis and views for explaining main reason to lead to injure. The type of lifting, heavy load and faster speed of lifting are three important reasons of injure. In this paper we emphasize mechanical principle and internal regulation of movement and try to obtain appropriate mechanical explanation about above problems. For convenience of analysis and calculation we suppose that the lifting action is bake typical lifting. The model included two segments with a load concentrated mass. These segments were: B_1—a load, B_2—head and trunk, B_3—legs and feet. The segment was considered as a rigid body (Figure 1).The

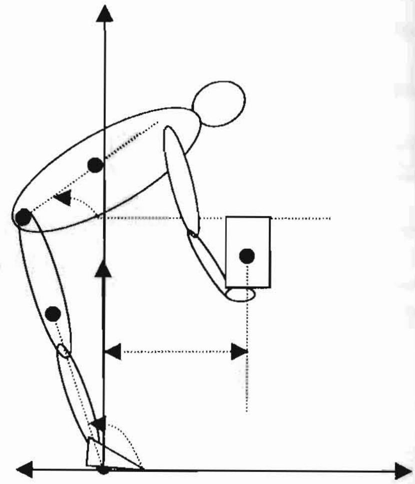

Figure 1 The model of back typical lifting.

link point between two rigid bodies could be simulated as a joint. We defined that the masses of B_1, B_2. B_3 are m_1, m_2, m_3 respectively. The moment of inertia of B_2, B_3 around their mass centers are J_2, J_3. The position of mass centers of B_1, B_2, B_3 are $C_1(x_1, y_1)$, $C_2(x_2,y_2)$,$C_3(x_3,y_3)$respectively. The position of joint between B_2 and B_3 is O_1. According to the property of lifting we assumed simulated model moves in planer coordinate system O-xy. Origin of coordinate O is located at the center of foot. $\vec{r}_2$ $\vec{r}_2^{\,'}$ are the vectors from O_1 and O to centre of B_2 respectively. $\vec{r}_3$ is a vector from O to centre of B_3, $\vec{l}$ is a vector from O to O_1. Consideration that B_1 rise vertically during lifting, we can assume x_1=b (constant) f, N respectively are horizontal and vertical constrained forces from ground. Then we can derive the equations of the movement based on theoretical dynamics

$$m_2\ddot{x}_2 + m_3\ddot{x}_3 = f \quad (1)\text{ a}$$

$$m_1\ddot{y}_1 + m_2\ddot{y}_2 + m_3\ddot{y}_3 = N - (m_1 + m_2 + m_3)g \quad (1)\text{ b}$$

$$J_2\ddot{\alpha} + J_3\ddot{\theta} + m_2\frac{d}{dt}(\vec{r}_2^{\,'} \times \dot{\vec{r}}_2^{\,'}) + m_3\frac{d}{dt}(\vec{r}_3 \times \dot{\vec{r}}_3) + m_1 y_1 x_1 = -(m_1x_1 + m_2x_2 + m_3x_3)g \quad (1)\text{ c}$$

Where the angles α, θ are from x axis to trunk and leg as general coordination respectively. Then, we can write:

$$x_1 = 0 \quad \dot{x}_1 = \ddot{x}_1 = 0 \quad y_1 = eh \quad \dot{y}_1 = e\dot{h} \quad \ddot{y}_1 = e\ddot{h}. \ (e \text{ is unit length})$$

$$x_2 = l\cos\theta + r_2\cos\alpha \qquad y_2 = l\sin\theta + r_2\sin\alpha$$

$$\dot{x}_2 = -l\dot{\theta}\sin\theta - r_2\dot{\alpha}\sin\alpha \qquad \dot{y}_2 = l\dot{\theta}\cos\theta + r_2\dot{\alpha}\cos\alpha$$

$$\ddot{x}_2 = -l\ddot{\theta} - l\dot{\theta}^2\cos\theta - r_2\ddot{\alpha}\sin\alpha - r_2\dot{\alpha}^2\cos\alpha \qquad \ddot{y}_2 = l\ddot{\theta}\cos\theta - l\dot{\theta}^2\sin\theta + r_2\ddot{\alpha}\cos\alpha - r_2\dot{\alpha}^2\sin\alpha$$

$$x_3 = r_3\cos\theta \qquad y_3 = r_3\sin\theta$$

$$\dot{x}_3 = -r_3\dot{\theta}\sin\theta \qquad \dot{y}_3 = r_3\dot{\theta}\cos\theta$$

$$\ddot{x}_3 = -r_3\ddot{\theta}\sin\theta - r_3\dot{\theta}^2\cos\theta \qquad \ddot{y}_3 = r_3\ddot{\theta}\cos\theta - r_3\dot{\theta}^2\sin\theta$$

$$\frac{d}{dt}(\vec{r}_2^{\,'} \times \dot{\vec{r}}_2^{\,'}) = -\ddot{x}_2y_2 + \ddot{y}_2x_2$$

$$\frac{d}{dt}(\vec{r}_3 \times \dot{\vec{r}}_3) = -\ddot{x}_3y_3 + \ddot{y}_3x_3 \quad (2)$$

Considering the relationship among θ,α, h during practical lifting, we suppose: There exist the differential constraints: $\dot{\theta} = -k\dot{\alpha} = -p\dot{h}$ If the boundary is θ=120°-90°.

Substituting (2), into (1) and simplifying, we obtained:

$$f = [2m_2r_2\cos 2\theta - (m_2l + m_3r_3)\sin\theta]\ddot{\theta} - [4m_2r_2\sin 2\theta + (m_2l + m_3r_3)\cos\theta]\dot{\theta}^2 \quad (3)$$

$$N = [\frac{24}{5\pi}m_1e + 2m_2r_2\sin 2\theta + (m_2l + m_3r_3)\cos\theta]\ddot{\theta} + [4m_2r_2\cos 2\theta - (m_2l + m_3r_3)\sin\theta]\dot{\theta}^2 + (m_1 + m_2 + m_3)g \quad (4)$$

$$[H_1(\theta)]\ddot{\theta} + H_2(\theta)]\dot{\theta}^2 = H_3(\theta) \quad (5)$$

Where

$$H_1(\theta) = -2J_2 + J_3 + m_2l^2 + m_3r_3^2 - 2m_2r_2^2 - m_2r_2l\cos(\alpha - \theta) + m_1b(\frac{24}{5\pi})$$

$$H_2(\theta) = 3m_2r_2l\sin(\theta - \alpha)$$

$$H_3(\theta) = -[m_1b + m_2(l\cos\theta + r_2\cos\alpha) + m_3r_3\cos\theta]g$$

Substituting it into (9) we can obtain first order differential equation

$$\frac{1}{2}\frac{dy}{d\theta}[H_1(\theta)] + H_2(\theta)]y = H_3(\theta) \quad (6)$$

Solving (10), we obtained analytic function.

$$y=\frac{K}{(A-\cos3\theta)^2}[AB\theta+AD\sin\theta+\frac{AE}{2}\cos2\theta-\frac{B}{3}\sin3\theta-\frac{D}{4}\sin2\theta-\frac{D}{8}\sin4\theta-\frac{E}{10}\cos5\theta+\frac{E}{2}\cos\theta+C] \quad (7)$$

Where $K=\frac{-2g}{m_2 r_2 l}$ $A=\frac{-2J_2+J_3+m_2 l^2+m_3 r_3^2-2m_2 r_2^2+m_1 be(\frac{24}{5\pi})}{m_2 r_2 l}$ $B=m_1 b$

$D=m_2 l+m_3 r_3$ $E=m_2 l r_2$ C = const

In order to further analyze internal force and moment at hip, we separated B_3 from this system. (Figure 2)Defined that N_x, N_y are horizontal and the vertical internal constrained forces respectively at hip. M is internal constrained moment at the hip. We can obtain these equations.

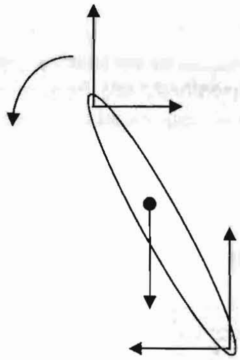

Figure 2 The model of separated body.

$$m\ddot{x}=f+N_x$$
$$m\ddot{y}=N-N_Y-m_3 g \quad (8)$$
$$J\ddot{\theta}=-Nr_3^2\cos\theta+fr_3^2\sin\theta+N_Y r\cos\theta-N_X r\sin\theta+M$$

Assumed the entire mass of B_3 is located at midpoint.
Substituting (7) (8) into (12).we got solutions

$$N_x=-f-m_3 r_3[(\sin\theta)\ddot{\theta}+(\cos\theta)\dot{\theta}^2]$$
$$N_y=N-m_3[g+(r_3\cos\theta)\ddot{\theta}+(r_3\sin\theta)\dot{\theta}^2] \quad (9)$$
$$M=\frac{J_3}{r_3}\ddot{\theta}+r_3(N+N_y)\cos\theta-r_3(f+N_x)\sin\theta$$

For convenience of numerical calculation, we assumed some approximate formulas according to Hanavan's report.:
m1=m2=m3=35 Kg=m

$l=2r_2=2r_3=4b=2r=0.9m$ $J_2=J_3=1/3mr^2$

Substituting (9) into (8), we obtained numerical solutions of $\dot{\theta}^2$, $\ddot{\theta}$ .Defined angle of hip β (between trunk and leg)

$\beta=\alpha+\pi-\theta$

We obtained numerical solutions and figures phase plane graph of $\dot{\beta}$, $\ddot{\beta}$ (Figure 3-4)

By equations (3) (4) (9), we obtained numerical solutions of Nx, Ny and M (Figure 5-7)

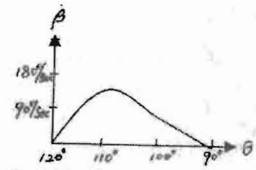

Fig 3. the curve of angular velocity $\dot{\beta}$ in phase plane

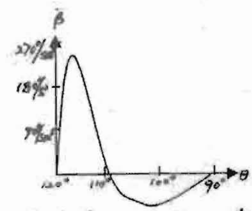

Fig 4 the curve of angular acceleration $\ddot{\beta}$ in phase plane

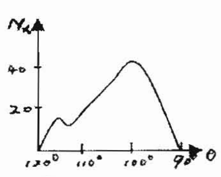

Fig 5 the curve of horizontal constrainted force at the hip

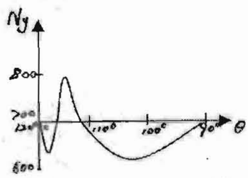

Fig 6 the curve of vertical constrainted force at the hip

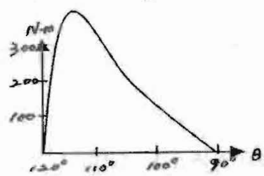

Fig 7 the curve of internal moment at the hip

RESULTS AND DISCUSSION: After obtaining these solutions we can get some results as follows: We obtained maximum peak values of some functions in above curve and calculation.

(1) $\dot{\beta}$=168 °/sec, $\ddot{\beta}$=426 ° /sec^2, Nx=42 N, N y=832 N, M=351 Nm

These data are smaller than the data from the references (Lei Ling, 2000; Zhu Liping, 1998). Because we assumed the process of lifting is smooth. Therefore we can think the theoretical model in this paper is an optimum type of lifting and a good supplement of experiments.
(2) By 8 equations it shows that the increment of the load at the hip has positive correlation with angular acceleration $\ddot{\theta}$ and negative correlation with angular velocity $\dot{\theta}$ The result indicates increasing angular acceleration is the essential reason of the increment of the load at the hip.
(3) According to the results of calculation the knee typical lifting is better than the back typical lifting in quantities analysis. Because the essential difference between two typical lifting is that vector $\bar{r}_2$ $\bar{r}_3$ of knee-type is smaller than back-type. Hence the angular acceleration $\ddot{\theta}$ will decrease in the knee-type. Through calculation of above method .So we can think that the knee typical lifting is better one in theory.
(4) Comparing the parametric curves of this paper with other curves from experiments, the later display singular point in the curves it is caused by movement when the lifting suddenly accelerate. The curves are smooth and differentiable in this paper. Besides, the results of analytic function are obtained in this paper. It is more valuable than numerical results for further research of mechanical principle.

CONCLUSION: Based on some analyses above, we can conclude as follows: First, the research of lifting in dynamic model is necessary and valuable. Second, it is helpful to explore mechanical principle of movement and it is also a good supplement to the experimental method .Third, it proves that the key factor which influences the loads at the hip is the angular acceleration $\ddot{\beta}$ (hip angle) in lifting. Finally, the better way to avoid injury is smooth type of lifting.

REFERENCES:

Andris Freivalds et al. (1984). A dynamic biomechanical evaluation of lifting maximum acceptable load. J. *Biomechanics* :17:251-262.

Chaffin-DB. Page-GB. (1994). Postural effects on biomechanical and psychophysical weightlifting limits. *Ergonomics* Apr.37(4) 663-76.

Gagnon, M. et al. (1991). Muscular mechanical energy expenditure as a process for detecting potential risks in manual materials handling. J. *Biomechanics*:24: 191-203.

Gagnon, D. & Gagnon, M. (19920. The influence of dynamic factors on triaxial net moment at the L5/S1 joint during asymmetrical lifting and lowering. *J Biomechanics*: 25: 891-901.

Gagnon, M. et al. (1996). Knee movement strategies differentiate expert from novice workers in asymmetrical manual materials handling *J. Biomechanics*,:29:1445-1453.

Lei Ling. (2000). Ergonomic basis of low back injury in foundry workers Academic dissertations of Furan University.

Zhu Liping. (1998). Biomechanical analysis of the lifting action Academic dissertation of Beijing physical education University.