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Modelling energy expenditure of a brick layer at various postures

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Abstract

Energy utilisation at work in the labour-intensive building industry is of prime importance to contractors who match people to jobs. This paper provides an insight into modelling energy expenditure in a specific task, namely brick laying in various postures. It therefore takes previous "generic" biomechanical-energy prediction models, and makes the case for applying and adapting broader theoretical models to a specific occupational task. This refinement of established models provides a meaningful and valuable contribution to interpreting and predicting energy expenditure during a defined occupational task – brick laying. Results obtained show that in the standing position, fewer muscles are brought into action. For the sitting position, the muscles are more relaxed, relieving the bricklayer of stress, but the center of gravity is still lower than the standing position. In the case of squatting, there is a lot of strain in the body by considering the muscles of the arms, legs, and back resulting in more energy released in the body. The bending position has repeated movement of the muscles at the back and the center of gravity varies. Thus, this research on energy expenditure in brick layers may be of interest to ergonomists and those interested in biomechanical-energy modelling.

Keywords: Work posture, bricklayer, energy, expenditure, calorific value

1 Introduction

Energy expenditure has been a dominant research focus in the ergonomics literature for several decades and has recorded successful studies in vacuum cleaning (Mengelkoch and Clark, 2006), wildland fire fighting (Heil, 2002), and long-haul cabin crew management (Barnes, 1973). Energy expenditure has been linked to a number of other activities, which include inhalation rates (Stifelman, 2007), work postures (Tarriere and Andre, 1970), physical stress (de Looze et al., 2001) and mechanisation of physical load (Burdorf et al., 2007). Specifically, energy expenditure plays a significant role in the achievement of productivity goals of building bricklayers since the work of building construction is labour-intensive and requires personnel with stamina and ability to work for long hours. Thus, the physique of the bricklayer and a skillful manipulation of postures for work (which may involve manipulation of joint movement and muscle forces erection during bricklaying activities) are important elements that may promote productivity at work (Bespalov et al., 1996). The current work focuses on the development of an energy expenditure framework for the bricklayer under different postures of squatting, sitting, bending and standing. This would provide useful information on the appropriate posture to take for different jobs, and the estimate of energy needed for such jobs. In real life, energy may be supplied as mechanical or other forms. If specified mechanical energy measurements are reliably and accurately predicted from metabolic energy expenditure, several benefits would be realised in regard to optimising energy utilisation at different postures. The establishment of a metabolic energy predictor would also allow the energy aspect of bricklaying activities to be studied through computer simulation (Foerster et al., 1995). However, this study focuses on finding out the most suitable, efficient and less tedious posture that the bricklayer could take in order to carry out the daily activity with minimum calories being expended from the body.

In a review of the measurement of mechanical energy associated with human movement, Winter (2000) notes that consensus is lacking in regard to the best method of calculating mechanical energy expenditure (see also Foerster et al., 1995). Perhaps, a factor contributing to the lack of consensus in methodology adoption is the variation in environments where application of study could be made. In this work, the environment is distinct from those recorded in the literature, being from the tropics, and therefore justifies a methodology tailored to the needs of the tropics.

Although considering all the actions involved in brick laying activities, the solution to the model formulation of energy expended by brick layer at work seems complex, however, a simplified version of the energy expended by the bricklayer is proposed to serve as a starting point for reformulation and improvement in the methodology. The repetition of actions in bricklaying activities is a helpful insight when viewing this series of repeated actions as a case for vibration in motion. In relating energy to performance, a relationship is first established between energy input and energy output using the principle of conservation of energy. The principles of virtual work and classical mechanics could also be adapted to provide potential solutions concerning the energy input/output problems of a bricklayer at work.

The principle of conservation of energy, which is adapted to the bricklayer's activities, relates to change in the energy of the bricklayer. This is equal to the net transfer of energy into the system by a heat interaction plus net transfer of energy into the system by work interaction. The second principle used (virtual work), considers the virtual work done by all external active forces (other than the gravitational and spring). Basically, the human body, which consists of over 600 muscles, making up about half the total mass of the body, is evaluated in terms of calories of the stored energy valve from food. From the principle of conservation of energy, the calories from food intake is equated to the calories of energy that the body uses.

The following provides a review of some important studies in energy expenditure in order to identify important gaps. Markowski et al. (2007) and Stifelman (2007) presented two independent studies on energy expenditure. The first of these references is about energy expenditure in refrigeration units, while the second discusses techniques to measure human energy expenditure in bricklayers. Neither of these two references address the issue of energy expenditure in bricklayers. Thus, the scientific study of energy expenditure in bricklayers remains an open research area that warrants investigation. In two separate investigations, the focus of McGill and Norman (1987) and Dennis and Barret (2002) have been to define values to which MAL should be for both erector spinae muscle group against that recommended by NIOSH.

The abundant documentation on energy expenditure justifies extensive interest in the proper management of enery at work for optimum performance (Bespalov, 1996; Umberger, 2003). Bespalov (1996) compared the mechanical energy expenditures (MEEs) of two human lower extremity models with different sources of mechanical energy. Foerster et al. (1995) recorded the measurements of metabolic energy consumption and free-walking velocity of four persons with trans-femoral amputations with variations of prosthesis mass and mass distribution.

The paper is sectioned into the following: introduction, methodology, case study, discussion of results, and conclusion. The introduction provides an insight into the significance of the problem and its definition. It also discusses the need to close the knowledge gap in the application of a "generic" model to a specific occupational task. Section 2 presents the methodology, which provides the framework for the presented approach. In section 3, a case study is illustrated to verify the application of the model presented in a previous section. Section 4 discusses the results. Section 5, the final section, provides concluding remarks.

2 Methodology

2.1 Definition of terms

S calorific value of energy
Q energy expended in each position
T energy left after work
Q_A energy expended in standing position
Q_B energy expended in sitting position
Q_C energy expended in squatting position
Q_D energy expended in bending position
δU sum of the work done by all active forces other than spring (muscle) forces and weight forces.

δVe work done by muscle
δVg work done by weight
ω weight of the bricklayer
t_1 initial temperature of the room
t_2 final temperature of the room
b weight of lagged room with water for cooling
a weight of lagged room
$(47 - t_2)^oC$ Fall in temperature of solid
m mass of the bricklayer
s distance moved by the brick layer
$(t_2 - t_1)^oC$ Rise in temperature of room
$(b - a)g$ Mass of water in room
$(t_2 - t_1)^oC$ Rise in temperature of water
E_1 energy expended in the hands
E_2 energy expended in the legs
E_3 energy expended in the head during movement

E_4 energy expended by the body
$\sum F$ resultant of all forces acting on the particle P
M_o moment about the origin 0

2.2 Model development

The starting point is to equate energy expenditure and work done. Work done is when a force is applied to a body and the body moves in the direction of the force. Thus, mathematically, Work done = Force × distance moved by point of application of force in direction of force. This is expressed as: Work done by F = F × s (1)

When the force is applied gradually so that its magnitude varies from zero to a maximum value F, then the average force is ½F and therefore, Work done = ½Fs (2)

If we consider the spring system, the spring stiffness constant is of importance in considering the limit to which the spring could endure before breaking. Similarly, the spring stiffness constant could be equivalent to the point of maximum energy potential in the bricklayer beyond which the bricklayer would refuse to continue to work and seek rest for a while. As opposed to what happens to the spring in which it may not be restored to its original state, the bricklayer may regain stability after short rest to restart work. Since the load per extension of the spring system is measured over the distance that the load travels, similarly, for the bricklayer, the load per extension is recorded, and the appropriate formula stated as F = Sx, where F represents the force, S, the load carried by the bricklayer, and x, the working range distance over which the bricklayer travels.

Then work done = average load × extension = ½F × x = ½Sx × x = $½Sx^2$ (3)

Thus, the above is the potential energy of the spring. During an increase in the compression of the spring from x_1 to x_2 the work done equals its change in elastic potential energy, $\Delta Ve = \int_{x_1}^{x_2} kx\,dx = \frac{1}{2}S\left(x_2^2 - x_1^2\right)$ during the virtual displacement δx of the spring (muscle), the virtual work done on the spring is the virtual change in elastic potential energy. Winter (2000) summarises the variety of approaches used by today's scientist to understand muscle function and the mechanisms of contraction. Winter (2000) refers to positive work being done during a concentric muscle contraction and negative work when a muscle is acting eccentrically i.e. when it is being contracted. During bricklaying activities i.e. when a bricklayer tends to lift an object towards self, muscle compression occurs such that the force applied to lift the load tends to compress it. This force, which may be applied in an anticlockwise direction, makes the muscle to relax from $x = x_2$ to $x = x_1$. This change (final minus initial) in the potential energy of the spring is negative. When we have a muscle in tension rather than compression, the work and energy relations are the same as those for compression. When the muscle is being stretched there is force doing positive work.

Now, considering the energy equation: From the conservation of energy, Work done by all other active forces = work done by muscle + work done by weight

$$\delta U. = (\delta Ve + \delta vg) : \theta \qquad (4)$$

$$M = \text{Moment about a point}$$
$$M = \text{Force} \times \text{perpendicular distance}$$
$$M = F \times d \qquad (5)$$

from the basic knowledge of dynamics with respect to vectors

Moment equation about a fixed point, $\Sigma M = \left(\frac{dH}{dt}\right)_{XYZ} + \Omega \times H$

$$\Sigma M_o = r \times \Sigma F = r \times m\dot{v} \qquad (6)$$

Newton's Second Law $\Sigma F = m\dot{v}$

$$\dot{H}_o = (\dot{r} \times mv) + (r \times m\dot{v}) = (v \times mv) + (r \times m\dot{v}) \qquad (7)$$

The term $(v \times mv)$ is zero since the cross product of parallel vectors is identically zero.

$$\Sigma M_o = \dot{H}_o \qquad (8)$$

From equation (7), it states that the moment about the fixed point 0 of all forces acting on m equals the time rate of change of angular momentum of M about 0. It is noted that the moment about the origin is indicated as 0. The justification is that conventionally, the principle of moment calculation demands that moments about an origin are made. However, if a different value is chosen, a dislocation of results may arise, which would give imprecise results. For example, the MAL for the erector spinae according to NIOSH is 0.05m. McGill and Norman's study (1987) examined the erector spinae muscle group using the individual muscles and found that the MAL for the erector spinae should be 0.075m rather than the previous accepted 0.05m. This 50% increase of the MAL is determined by reassessing all the active extensor tissues that act under an equivalent MAL. In another study, the MAL of the erector spinae muscle group was 0.06m (Dennis and Barrett, 2002). Consequently, since no consensus of opinion exists on the specific value chosen, it may be necessary to adopt the traditional approach applicable in the principle applied.

We know that gravitational potential energy: Vg = mgh. By the principle of conservation of energy, Heat lost by the bricklayer (in terms of sweat) during hot conditions is equivalent to the heat gained. Thus,

From the expression $mS(47 - t_2) = (b - a)(t_2 - t_1) + 0.1a(t_2 - t_1)$,

$$S = \frac{(b - a)(t_2 - t_1) + 0.1a(t_2 - t_1)}{m(47 - t_2)} \text{ cal/g/deg c} \qquad (9)$$

The major parts that came into play in the human body (bricklayer) is the arm, neck, legs and some body movements. In calculations, the muscles are assumed to have:

- Spring stiffness
- Initial compression
- Moment about a point
- Weight due to gravity

The energy utilized by combining all the actions of the muscles should be compared with that of the specific caloric value S, and then equating all the energy to calorific values.

E_1 = work done by muscle + work done by weight =
(½ × stiffness × initial compression^2) + mgh
E_2 = work done by muscle + work done by weight =
(½ × stiffness × initial compression^2) + mgh
E_3 = work done by muscle + work done by weight =
(½ × stiffness × initial compression^2) + mgh

The expenditure of a bricklayer is best achieved by comparing the calorific value of the energy in the bricklayers body to that which has been expended.

$$S - Q = T \qquad (10)$$

2.3 The human body as a mechanical system

The human body can be likened to a mechanical system in so many ways. The human body consists of more than six hundred muscles and together, they make up nearly half the total mass of the body. Each muscle is made up of specialized cells called muscle fibres. These fibres contract or shorten when they are stimulated. The muscle needs energy to perform the work required for contraction and expansion. This energy is supplied by the food we do consume which contains calories. A caloric is the unit used to measure the energy value of food and the energy used by the body to maintain normal functions. From the principle of conservation of energy, calories from food intake = calories of energy the body uses. This can be likened to a perfect system thereby allowing the body weight to remain constant. The Body Mass Index (BMI) is commonly used to determine desirable body weights. This plays a very important role in determining the human energy capacity. A bricklayer with a small body will be limited to some kind of work and has an average Body Mass Index, defined as:

$$BMI = \frac{\text{Weight of the bricklayer}}{(\text{Height of the bricklayer})^2} = kg/m^2$$

The muscles of the human body act as springs when compared to a mechanical system. They are in constant contraction and expansion having their force (F) attacked and spring constants (k). The aim of a bricklayer is an example of a mechanism in constant contract and expansion.

The fourth assumption is that the energy expended for each position is known. All the bricklayers intend to start at the same time. It is required to determine the energy expenditure of the bricklayer assuming a weight of 700N. The initial temperature of the test room is 27°C. The final temperature of the room is 31°C. The weight of the lagged room is assumed to be 90kg. In addition, the weight of the lagged room with water for cooling is 110kg. It is also desired to compare the various energy expenditure of the bricklayer with that of that stored in the body of the bricklayer. In solving this problem, the expression for energy expenditure is first stated while the component parameters are determined.

The formula for specific calorific value, $s = \frac{(b - a)(t_2 - t_1) + 0.1a(t_2 - t_1)}{m(47 - t_2)}$.

However, we are given m = 70kg, t_2 = 31°C, t_1 = 27°C, a = 90kg, and b = 110kg. Thus, in applying the formula in calculating S, we obtain:

$$s = \frac{(110 - 90)(31 - 27) + 0.1(90)(31 - 27)}{70(47 - 31)} = 0.10357.$$

Since 5 calories will raise its temperature by 1°C, and assuming that the temperature rose by 20°C, the amount of calories per degree Celsius is calculated, and used to calculate the total calories = 5 x 20 x 0.10357 = 10.357 calories. Thus, energy in the bricklayer's body = 10,357 calories x 4.2 joules = 43.5 joules. From our analysis and assumption, we note that four positions are possible. These are standing, sitting, squatting and bending. For the standing position, fewer muscles are brought into action. It is the action of the muscles in the arm and the weight of the body that are in expansion and contraction. Hence, centre of gravity is high. Thus, $\delta Ve + \delta Vg = Q_A$ = 28.1kg. For the sitting position, the muscles are more relaxed, relieving the bricklayer of stress but the centre of gravity is lower than the standing position. However, the muscles still perform at an expansion and contraction mode. Thus, $\delta Ve + \delta Vg = Q_B$ = 27.0kg. For the squatting position, there is a lot of strain in the body considering the muscle of the arms, legs and back.

4 Discussion of results

The food that we consume plays an important role in the energy expended by a bricklayer in daily activities. When the bricklayer is resting, he or she consumes little calorie, however, more calorie is required for a manual worker. From the case study considered in the previous section, a heavy worker (bricklayer) requires about 4500 calorie per day. The human body is assumed to be a mechanism in a sequential motion resulting in contraction and expansion of the muscles, and the initial work done, known as strain energy is equivalent to what is stored in the spring of mechanical systems. The weight of the bricklayer above the ground contributes to the energy expended by the bricklayer. This is equivalent to the potential energy of the bricklayer. For the standing position (case study 1) where s = 43.5kJ, Q_A = 28.1kJ, the value of τ = 15.4kJ reflects the amount of energy still conserved in the body of the bricklayer. However, the time taken for the project completion is 8hrs 30mins.

For the sitting position of the bricklayer, the case study II, s = 43.5kJ, Q_B = 27.0kJ, τ = 16.5kJ, which indicates that the bricklayer still conserves 16.5kJ of energy in the body. The total time for completion is 12hrs 45mins. Case III considers the squatting position, where s – 43.5kJ, Q_C = 33.2kJ and τ = 10.3kJ, indicating that the bricklayer conserves 10.3kJ of energy in the body when squatting to do the bricklaying job. The total time taken for completion is 8hrs 55mins.

The bending position, case IV, shows that s = 43.5kJ, Q_D = 31.05kJ and τ = 12.45kJ, indicating that the bricklayer conserves 12.45kJ of energy in the body. By comparing the energy expended by the various positions of the body, the following analysis is relevant. More energy is utilized by the bricklayer in the squatting position (i.e. 33.2kJ). This is followed by the energy utilized by the bricklayer in the bending position (i.e. 31.05kJ). The standing position demands lower energy, which is 28.1kJ. However, the minimum energy utilized by a bricklayer is the sitting position (i.e. 27.0kJ). The time to job completion is least for the standing position (i.e. 8hrs 30mins). Squatting follows this, which takes 8hrs 55mins. The bending position takes 9hrs 5mins, while the sitting position takes 12hrs 45mins.

5 Conclusion

In this paper, a mathematical model is formulated that determines the amount of energy of a bricklayer both at rest and at work. This aim is achieved when the human system is considered a mechanical system, which stores energy in it to do work. Similarities between the human system and the mechanical system that are explored in the model formulation include: (1) treating the human arm as acting as a lever; (2) the human muscles acting as various spring of different stiffness coefficient; (3) displacement of various lengths; and (4) energy due to position, etc.

Thus, the model adopts the principle of conservation of energy knowing that energy is converted from one form to another. It is noted that less energy is consumed during the sitting position compared to standing and other postures. However, it takes longer hours of job completion. The standing position is more ideal in carrying out an efficient energy utilization for maximum output. The model is useful in determining the energy stored within a body of different workers i.e. light and heavy physique workers. It also determines the amount of calories required for various manual labours in bricklaying. It may serve as a useful model for building contractors who desires to engage bricklayers that would produce sufficient output to justify their pay. Human nutritionists could also benefit from the model proposed here. Again, the model may be adapted to other work settings with minor modifications in the model structure.

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