MODELLING WELDING POSTURES IN A SMALL-SCALED ENTERPRISE

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ABSTRACT: *The purpose of this paper is to evaluate the personnel working in the welding process by analyzing them in different work postures, such as squatting, bending, and standing. An analytical method that critically considers human anatomy is used in this study. Within the scope of the research, it is assumed that the welding takes place on a broad workpiece in a vertical plane that allows access from different welding postures. The multiple forces involved due to the interactions between the muscles, tendons, ligaments and bones of the welder with the internal and external masses moved are comprehensively analyzed. The major forces analyzed are from the engineering viewpoint and attention is given to the forces crucial to equilibrium conditions at the work postures. The working postures of the welders in a small welding workstation in the squatting, bending and standing postures are analyzed for energy expenditure given the typical human anatomy dimensions considering the mass of the welding rod and other moving parts carried and the potential energy at the point of analysis of the welder. The results belonging to each work posture were given separately. In the case study, the total energy expenditure at the squatting, sitting, bending and standing positions are -36.8 kJ, -8.02 kJ, -15.32 kJ and -5.97 kJ, respectively. This indicates that squatting is the worst position regarding energy expenditure while the standing work posture gives the best energy expenditure. This paper indicates the usability of the analytical method in determining the energy expenditure at various work postures of the welder. By employing the analytical method at the welding workstation, the value and originality of the research are established.*

Keywords: *Energy expenditure, welder, mathematical model, workstation*

1.0 INTRODUCTION

Working postures are positions adopted by a worker while performing the assigned task [1, 2]. Surahma et al. [3] affirmed that it serves as a condition of work that strongly determines how effective work is accomplished. Although natural working postures are prevalent in traditional industries, and by extension, the welding workshop, unnatural working postures are unacceptable and often stimulate musculoskeletal problems in workers in the work field [2, 4]. Fadzil et al. [4] analyzed the potential of having musculoskeletal disorders in a group of students in a practical welding session at a Malaysian Polytechnic. Shahriyari et al. [5] reported the prevalence of musculoskeletal disorders (i.e. neck, shoulder, and back) in an Iranian population. Samples of these unnatural working postures, which are labelled as problematic and demanding are welding positions such as holding arms away from the body, squatting, holding arms above the shoulder heights for extended time, torso twisting, hunching or bending over, kneeling and looking upward for too long. Furthermore, the analytical study of welding postures is important because it presents a detailed and clear perspective of how the welding parameters interact and affect the outcome.

In adopting analytical solutions to the welding postural problem, costly experimental data are bypassed, guaranteeing cost-effective operations. Thus, in welding operations, particularly in energy expenditure aspects of welding, analytical solutions for welding postures are a new class of promising solutions with wide applications in several other jobs such as carpentry. The development of analytical solutions for the welder's postures comes with the need to unravel the welder as a body that is subjected to the principle of conservation of energy, obtained from the first law of thermodynamics [6]. Here, the body changes of the welder are visualized in terms of heat and work transfer where temperature is an issue in the analysis. Moreover, the body parts at various postures engage in velocity changes where angular velocity is a key requirement in the analysis, leading to the development of equations guided by moment of inertia, displacement of forces, and speed of movement of body parts among other issues. Unfortunately, detailed knowledge of the analytical perspective of welders in small-scale operations in the squatting, sitting, bending and standing positions is still largely absent in the literature, a useful source of information to predict energy expenditure in welders. Poor understanding of the energy expenditure of the welding at the different welding postures such as squatting, sitting, bending and standing introduces significant challenges in the management of the welding process and overcoming them could bring the following benefits to the welding system: Reduced low back pain, joint longevity, boosted energy and the enhanced mood of the welder. The following are some of the literature reviewed on the subject of the present paper.

Suman et al. [7] investigated musculoskeletal disorders in welders working within manufacturing industries in West Bengal, India. Very high prevalence rates of symptoms of musculoskeletal disorder in the bodies of welders was declared by the report. This was associated with work postural stress and work posture during welding. Ruengdech et al. [8] reported on a risk evaluation scheme for muscle injuries using artificial intelligence technology to evaluate the postures of electric welders using the evaluation scheme called the rapid entire body assessment (REBA) to establish injury causal factors to muscles. It was found that the scheme is effective in evaluating the electric welders' muscle injuries. Hsu et al. [2] analyzed the unnatural working posture in a water heater factory using the Ovako Working Posture Analyzing System and the Nordic Musculoskeletal Questionnaire for water heater production. The conclusion from the Ovako Working Posture Analyzing System is that for the operators, the head/neck and back were above AC3 in some workshops, a situation, which could trigger musculoskeletal symptoms. From the outcome of implementing the Nordic Musculoskeletal Questionnaire, the percentage of aches on the neck, lower back and shoulders was higher than in other parts of the body compared with the present study, the reviewed work has not attempted linkage of working postures to energy expenditure. More importantly, no reference to analytical solutions was observed in the work and welders are not mentioned at all in the study. Moreover, Isher et al. [1] analyzed the working posture of workers in the clothing industry using three principal methods such as PLIBEL, Ovako Working Posture Analyzing System and REBA. The study concludes that the REBA and OWAS approaches are reliable. The two approaches revealed that all departments being analyzed require ergonomic arrangements. Moreover, the cutting department critically requires ergonomic arrangement instantly (OWAS is 87.69 while REBA is 90.58%). The authors observed that the ergonomic analysis approach; which is the Ovako Working Posture Analyzing System has been repeated in two studies, indicating its popularity as a tool for working posture analysis. Yet, the study being reviewed here omits the issue of energy expenditure in the process and no information directly transferable to the welding process from the reviewed work is available. Thus, the analytical approach to working postures in the welding station has been ignored and presents an important gap to tackle in the literature.

Das et al. [9] adopted a completely different approach to analyzing work postures in welding stations compared with the previous reviews. Many studies have used survey and experimental approaches, including the adoption of assessment tools such as REBA (rapid entire body assessment) [8], RASMI (risk assessment system for muscle injuries) [8]. RULA (rapid upper limb assessment) [4], Das et al. [3] used as an analytical perspective, which is consistent with the approach adopted in the present study. Das et al. [9] approach was to attain a spread of intensity of stresses and Von–Mises stresses within various joints and muscles at work while welding. Surahma et al. [3] examined the postures of Las Manggaraya workshop workers at work with the tool called RULA. From the anthropometric data collected, it was established through the RULA method that very western and severe risk levels are associated with a 5/8 proportion of workflow processes. This implies the urgent need to change work postures at the earliest. Hariri et al. [10] conducted experiments to evaluate how welding fumes diffuse in the air towards welders while standing and sitting and welding aluminium plates using a dummy welder on a computer numerical control machine. It was reported that welding fume exposure to the welder standing was higher than when the welder was sitting.

Akanmu et al. [11] examined the working posture in floor framing for carpenters and how it is linked to musculoskeletal disorders, non-fatal injuries and body pains. The approach adopted in the wearable sensors to characterize ergonomic exposures of carpenters through measuring and examining their body movement data. It was found that severe risk impositions on the elbow, trunk and should due to the measuring, marking cutting out vent locations and while placing and nailing boards in position exists. Moreover, as this reviewed article is compared with the current study, it could be observed that the measurement approach adopted varies significantly from the analytical approach taken in the present study. Also, the issue of energy expenditure was not considered in the study. Ogunseiju et al. [12] analyzed the usefulness of a postural-assist exoskeleton (i.e. a passive exoskeleton) for adoption in tasks involving manual material handling. It was found that the exoskeleton introduced substantial discomfort for the worker whose movement range was reduced with the load-lifting task. While the utility of the work lies in the designer and innovators, little information could be obtained from the work on how energy expenditure could be extracted from it. Also, no link with the welder's postures was revealed in the study.

From the discussion earlier given, the purpose of this paper is to analyze the energy expenditure of the welder at various positions, namely squatting, sitting, bending and standing. The postural energy expenditure of the welder relative to positions in the gravitational field is analyzed as the muscle energy expenditure view from the anatomy of the welder. This article presents a fresh insight into the energy expenditure problem of the welder, providing a broad perspective of the welder's posture and energy expenditure from the thermodynamics and force computation perspectives.

Novelty of the study

The following describes the novel elements of the present study:

- This study introduces a new analytical structure for work postural examination, particularly the work postures of the welder in the squatting, sitting, bending and standing position, analyzing the forces required to actualize the work postures. This is a crucial area having little research in welding practices.
- While the different work postures have been extensively studied, this work uniquely analyzes the internal components of the human body (welder), exploring the energy and force equations, and providing actionable understanding for energy planning.
- The novelty of this study lies in the joint usage of systems' principles, human anatomical working systems and the laws of mechanics, providing a robust and reproducible analysis of the working postures, such as to be extended to allied work practices such as carpentry and auto mechanics.

2.0 METHOD

This work is concerned with the modelling of the energy expenditure at postures. While previous approaches have taken diverse perspectives such as considering the influence of temperature on work performance [13 - 15], their interest in developing the mathematical model is to apply the principle of conduction. However, at variance from the research, the conservation of energy is the guiding principle adopted at this stage. The general welding operation is first accounted for while adopting the principle of conservation of energy for all postures. Then, the different postures are taken as special cases of the general operation. Hence, the governing equations will be first derived before the different applications. Here, the starting point is to consider the conservation of energy of the welder as given by the first law of thermodynamics, which states that energy could be change from one firm to another as interaction occurs among the internal energy of the welder, the work done by the welder and heat produced during work by the welder [6]. Equation (1) is then accepted as valid:

$$\sum \delta Q + \sum \delta W = 0 \tag{1}$$

where dQ is the change in the heat exchange between a system and its surroundings.
dW is the change in the work done on or by the system. However, correlating the first law introduces a property of a system such that a change in its value is equal to the sum of the not heat and work transfers during any change of state.

A corollary of the first law introduced a property of a closed system such that a change in its value is equal to the sum of the net heat and work transfers during any change of state. Subscripts 1 and 2 represent state 1 and state 2 respectively. Thus, we have:

$$\sum_{1}^{2} \left(\delta Q + \delta W \right) = E_2 - E_1 \tag{2a}$$

$$Q_{12} + W_{12} = E_2 - E_1$$

E is the internal energy of the system, in this case the welder.

$$W_{12} = E_2 - E_1 - Q_{12}$$
$$◎W = ◎E - ◎Q \quad (2b)$$

Convention used:
All quantities into the system (welder) - positive.
All quantities out from the system (welder) into the surrounding- negative

Eqn. (2b) tells us in a nutshell that to obtain the network transfer (in other words the energy expenditure), we simply find the difference between the change in internal energy and the change in the heat transfer for any cycle or stage. From thermodynamics, we know that heat flows across the boundary of a system as a result of a temperature difference. Hence for a constant pressure process which models the constant atmospheric pressure of 1atm ◎ 100 kPa.

$$dQ = dh \text{ (constant pressure)} \quad (3)$$
$$dh - c_p dT \quad (4)$$
$$\text{Combining Eqns. (3) and (4): } dQ = c_p dT \quad (5)$$

But humans are homoeothermic. Hence, for a healthy welder, the body temperature does not change appreciably from about 37^{o}C = 310K.

Therefore,

$$dT ◎ 0$$

Hence from Eqn. (5), dQ ◎ 0 i.e. heat loss due to change in body temperature is negligible. But the body loses heat at constant temperature due to radiation of body heat and perspiration. Therefore Eqn. (2b) is modified to include these terms:

$$dW = dE - dQ - P_k$$
$$dW = dE - P_k$$
$$W_{12} = E_2 - E_1 - P_k \quad (6)$$

Where P_k is the heat transfer due to the body radiation and perspiration.

$$\text{i.e.} \quad P_k = H_{radiated} \text{ and } H_{sweat} \quad (7)$$

The body radiates heat given by Rogers and Mayhew [6]:

$$H_{radiated} = ◎◎AT^4◎t \quad (8)$$

The principal idea demonstrated in Equation (8) is the Stefan-Boltzmann law, which explains the computation of the heat transfer coefficient obtainable from a welder working in a workshop. Equation (8) states that the power of the radiation emitted by the welder’s body is proportional to the fourth power of the absolute temperature recorded for the situation. The heat of transformation required to evaporate the perspiration (sweat) is given by:

$$H_{sweat} = LMs \quad (9)$$

L = energy per unit mass required to vaporize sweat ◎ that of water = 2,256 kJ/kg
Ms = mass of sweat (kg)
Substituting Eqns. (8) and (9) into (7), we have:

$$Pk = \circledcirc\circledcirc AT^4 \circledcirc t + LMs \tag{10}$$

The above processes take place at a constant temperature as man is warm-blooded (homoeothermic) and his temperature remains fairly constant. Therefore Eqn. (10) into (6) becomes:

$$W_{12} = E_2 - E_1 - (\circledcirc\circledcirc AT^4 \circledcirc t + LMs) \tag{11}$$

Absolute values of E may be hard to obtain since calorific expenditures for individual persons may vary, but ◎E for a particular process will suffice. Also, since the time required for the event to take place is very important ◎t will be needed. Naturally, it follows that the quantity ◎E/◎t will be of immense importance in this analysis. Having obtained the P_k terms, the work proceeds to obtain the welder's internal energy terms concerning the mechanical properties.

Let Momentum P = mV and Kinetic energy K = ½ mV², m = mass (kg) and V = velocity (m/s),

$$PV = 2K \tag{12}$$

$$MVp = 2mK$$

$$p^2 = 2mK$$

$$2pdp = 2mdK$$

$$\frac{dp}{dK} = \frac{m}{p} \tag{13}$$

The rate of change of momentum with respect to kinetic energy is inversely proportional to the momentum and takes place in the direction of initial momentum. From the kinetic theory of matter, E_k ◎ internal energy where E_k = kinetic energy,

therefore Eqn. (13) can be rewritten: $\dfrac{d(mv)}{dE} = \dfrac{m}{mv} = \dfrac{1}{v}$

$$\int v\,d(mv) = \int dE \tag{14}$$

or $$v\frac{d(mv)}{dt} = \frac{dE}{dt};\ \ V.F = Power \tag{15}$$

or $$\frac{p^2}{2} = mK + C, \text{ When } p = 0 \qquad K = K_0^1$$

$$\frac{p^2}{2} = mK + mK_0^1$$

$$\frac{p^2}{2} = m\left(K + K_0^1\right) \tag{16}$$

Since mechanical properties are under consideration:

$$K + U = E \tag{17}$$

It follows that $K_0 + U_0 = E_0$

$$\frac{p^2}{2} = m\,(K - U_0 + E_0) \tag{18}$$

From Eqn. (14), $\int mvdv + \int v^2dm = E + C$

$$\int mvdv + \int v^2dm = E + E_0 \tag{19}$$

Combining Eqns. (18) and (19): $\int mvdv + \int v^2dm = E + \frac{p^2}{2m} + U_0 - K$

$$E = \frac{mv^2}{2} + K - \left(U_0 + \frac{p^2}{2m}\right) + \int v^2dm \tag{20}$$

But angular velocity is proportional to linear velocity at a constant radius $v = \omega r$, therefore

$$\int v^2dm = \int \omega^2 r^2 dm = \left(\frac{\omega^2 - 0}{2}\right)\int r^2dm = \omega_{avg}^2 \int r^2dm \tag{21}$$

where $\int r^2dm$ defines the mass moment of inertia. Therefore,

$$\int r^2dm = I \tag{22}$$

$$\int v^2dm = \omega_{avg}^2 I = \frac{\omega^2}{2} I \tag{23}$$

Substituting Eqn. (23) into (20):

$$E = \frac{m_0v^2}{2} + K - \left(U_0 + \frac{p^2}{2m}\right) + \frac{\omega^2}{2} I \tag{24}$$

To prevent disparity in results, it is assumed that the welding takes place on a broad workpiece in the vertical plane that allows access from the different welding postures (Figure 1). There are very many forces involved as a result of the interactions between muscles, tendons, ligaments and bones, with the internal and external masses moved [16]. A few relevant ones are selected. That is, those which from an engineering point of view are most critical to equilibrium conditions.

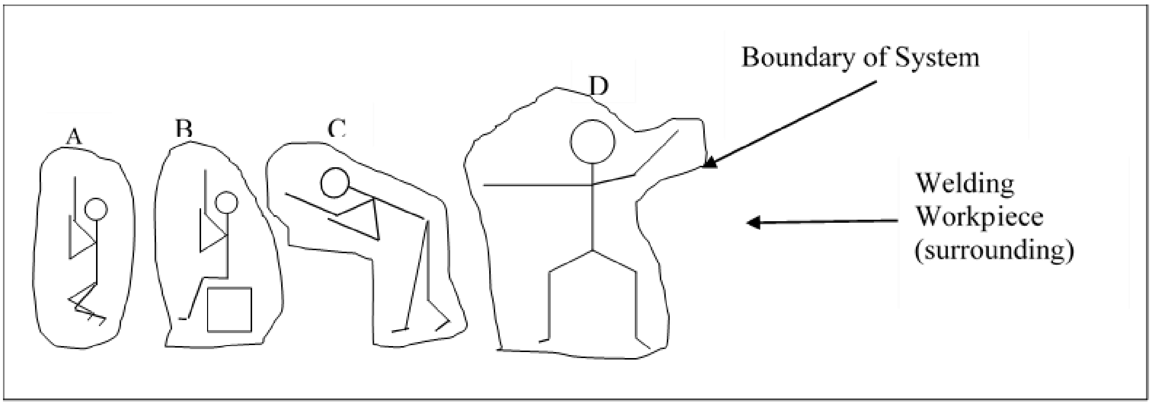

Figure 1: Different welding postures (Key: A- Squatting, B- Sitting on a support, C – Bending, D - Standing with arms outstretched)

Based on the human anatomy, the regions of greatest human expenditure will be at the Quadriceps and Patellar tendon [17]. Also, the lumbar portion of the spine is involved [17]. The justification for including the lumbar portion of the spine is that when squatting, the back is unsupported and the welder leans slightly forward to attain equilibrium, inducing high stresses on the spine [17].

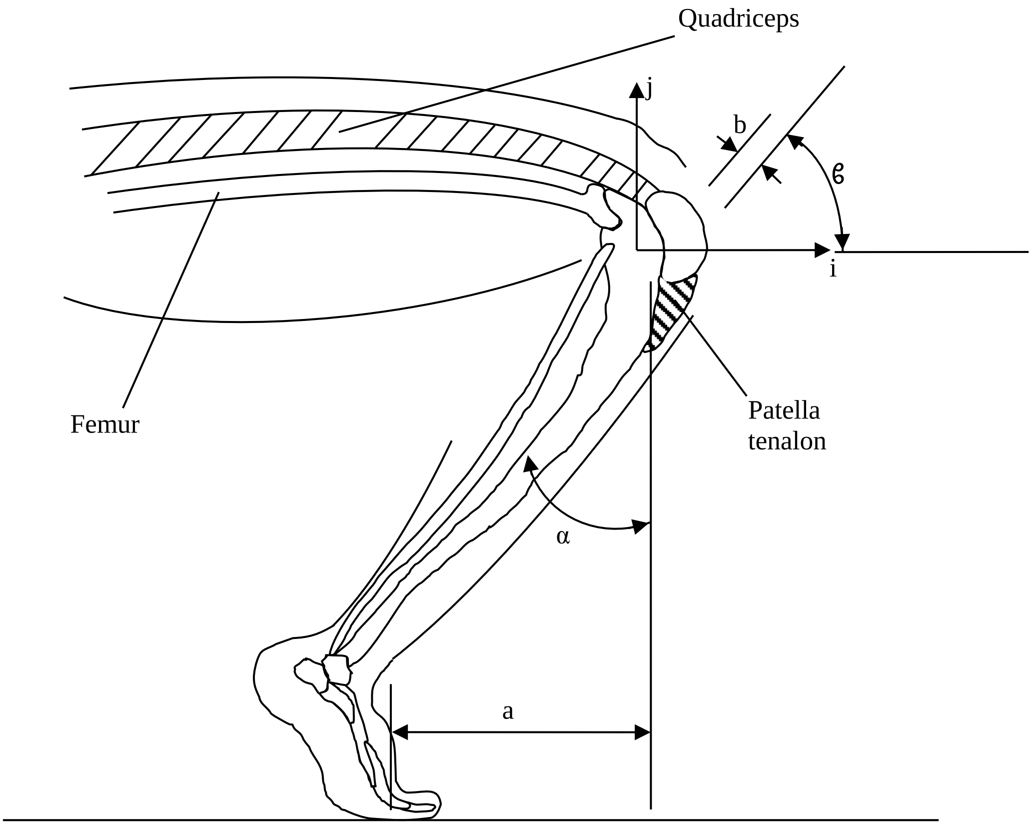

Figure 2: Human anatomy at quadriceps and patellar tendon (see also [17])

Let the weight of the welder be W. It is assumed that the weight of the welder is equally distributed on both feet (Figure 2). Also, the quadriceps contractions are transmitted to the patellar tendon, and the line of action of the patellar tendon force is along its midline inclined at angle ⊚ to the horizontal.

Applying the laws of mechanics [18], for equilibrium,

$$\sum \overrightarrow{M_0} = 0 \tag{25}$$

(i.e. the algebraic sum of moments about 0 is zero)

$$\text{Thus,} \quad -a\hat{i}\,\Lambda - \frac{w}{2}\hat{j} + \vec{b}\,\Lambda\,\vec{T} = 0$$

$$\vec{b}\,\Lambda\,\vec{T} = a\hat{i}\,\Lambda - \frac{w}{2}\hat{j}$$

$$\vec{b} = b\left(\sin\beta\hat{i} - \cos\beta\hat{j}\right)$$

$$\vec{T} = T\left(\cos\beta\hat{i} - \sin\beta\hat{j}\right)$$

$$-a\hat{i}\,\Lambda\, -\frac{w}{2}\hat{j} + \quad b\left(\sin\beta\hat{i} - \cos\beta\hat{j}\right)\;\Lambda\, T\;\left(\cos\beta\hat{i} - \sin\beta\hat{j}\right) = 0$$

$$-\frac{aw}{2}\hat{k} + \hat{k}\left(-Tb\sin^2\beta - Tb\cos^2\beta\right) = 0$$

$$-\frac{aw}{2}\hat{k} - Tb\hat{k} = 0 \text{ and } \quad T = \frac{aW}{2b} \tag{26}$$

Therefore, Patellar tendon force

$$T = -\frac{aW}{2b}\;\left(\cos\beta\hat{i} - \sin\beta\hat{j}\right)N \tag{27}$$

To obtain the reaction between the tibia and femur, we make use of another law of mechanics [18]. For equilibrium,

$$\sum \vec{F} = 0 \tag{28}$$

(i.e. algebraic sum of forces acting on the rigid body is zero).

$$\vec{R} + \vec{W} + \vec{T} = 0$$

where $\vec{R}$ is the reaction at point 0.

Knowing that the synovial fluid has a very low coefficient of friction the reaction acts at a normal to the tangent of contract between the tibia and femur which approximates a circular profile [17]. Therefore,

$$\vec{R} = R\;\left(\cos\alpha\hat{i} - \sin\alpha\hat{j}\right)N$$

$$-\frac{aW}{2b}\sin\beta\hat{j} = 0$$

$$\hat{i}:\quad R\cos\alpha - \frac{aW}{2b}\cos\beta = 0$$

$$\hat{j}:\quad R\sin\alpha - \frac{W}{2} - \frac{aW}{2b}\sin\beta = 0$$

$$R = \frac{aW\cos\beta}{2b\cos\alpha} = \frac{W}{2\sin\alpha}\left\{1 + \frac{a\sin\beta}{b}\right\} \tag{29}$$

Therefore, for equilibrium,

$$\frac{aW\cos\beta}{2b\cos\alpha} = \frac{W}{2\sin\alpha}\left\{1 + \frac{a\sin\beta}{b}\right\}$$

$$\frac{a\cos\beta}{b\cos\alpha} = \frac{b + a\sin\beta\sin\alpha}{b\sin\alpha}$$

$$a\cos\beta = \frac{b^2 + ab\sin\beta\sin\alpha}{\tan\alpha} \tag{30}$$

This is the criteria for the welder to remain in equilibrium when squatting (Figure 3). L_5 is the fifth and lowest vertebra of the lumbar region. We consider the disc between this vertebra and the uppermost vertebra of the sacrum region. The lumbar region supports the entire weight of the upper torso and the force load imposed on it. Let the ratio of the body weight the lumbar region supports to the total body weight be K [17].

$$\frac{Wu}{W} = K$$

$$Wu = KW \tag{31}$$

To obtain the compressive and shear forces on L_5, also to obtain the rectus muscle force [17]. Considering the L5 at the lower back of the welder, two types of forces usually occur there, notably, the Shear force and the compressive force. The magnitude of these two forces at the lower back of the welder is a function of the degree to which the welder bends, the weight of the metal carried for joining and the level of the task performed by the welder. It is common the literature to find the Shear force to range from 0.2 to 0.9 kN while the compressive forces usually vary from 0.4 to 10 kN (Afshari et al., 2018). For equilibrium, Eqn. (25) holds [17]:

$$\sum \overrightarrow{M_o} = 0$$
$$\vec{c} \wedge \vec{F} + \vec{d} \wedge \overrightarrow{Wu} + \vec{e} \wedge \vec{L} = 0$$
$$-c\hat{i} \wedge -F\hat{j} + d\hat{i} \wedge -kw\hat{j} + e\hat{i} \wedge -L\hat{j} = 0$$
$$cF\,\hat{k} - dkw\hat{k} - eL\hat{k} = 0$$
$$\hat{k}: \quad F = \frac{dkw + eL}{c}$$

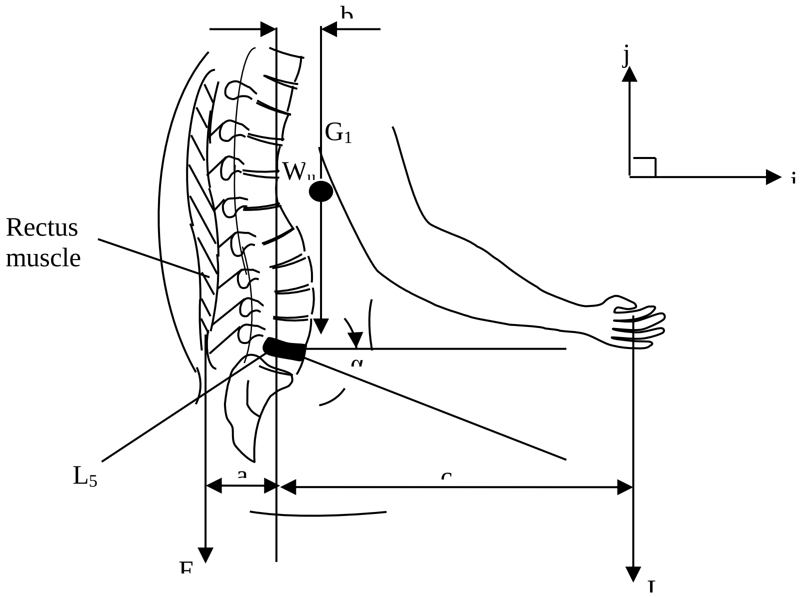

Figure 3: Human anatomy at the lumbar region (see also [17])

Furthermore, there are many symbols used in Figure 3, which are explained here. For instance, the symbol L5 occurring at the lower back of the welder is the fifth lumbar vertebra. It occupies the lowest position with four bones, namely L1, L2, L3 and L4 appearing before it. Also, in Figure 3 is the rectus muscle that runs vertically down at the form of the welder's abdomen.

Hence the force exerted by the rectus muscle will be: $\left(\frac{dkw + eL}{c}\right)\hat{j}\,\mathrm{N}$ (32)

From Eqn. (32), the term eL is very critical to the welder's safety. Since other terms are constants but eL is the product of the load and the displacement from the lumbar region. An increase in this term will seriously stress the rectus muscle.
Using Eqn. (28) to obtain the reactive forces on L_5.

$$\sum \vec{F}_{net} = 0$$

$\vec{R}$ is the reaction at L_5

$$\vec{R} = Rx\hat{i} + Ry\hat{j}$$

Compressive force on L_5: $\left|\vec{F}_c\right| = R_x \sin\theta + R_y \cos\theta$

Shear force on L_5: $\left|\vec{F}_s\right| = R_x \cos\theta + R_y \sin\theta$

$$\vec{R} + \vec{F} + \vec{W}u + \vec{L} = 0$$

$$\vec{R} = \left(\frac{dkw + eL}{c}\right)\hat{j} + kw\hat{j} + L\hat{j}$$

$$\hat{i}: \qquad R_x = 0$$

$$\hat{j}: \qquad R_y = \frac{dkw + eL}{c} + kw + L$$

$$\vec{R} = \left\{\frac{dkw + eL}{c} + kw + L\right\}\hat{j} \; (33)$$

$$\vec{F}_c = \left|\vec{R}\right| \cos\theta \quad \text{since } R_x = 0 \tag{34}$$

$$\vec{F}_s = \left|\vec{R}\right| \sin\theta \quad \text{since } R_x = 0 \tag{35}$$

Sitting

The seat relieves the patellar tendon from its tension since $\vec{W}$ acts normally on the seat and is not transmitted to the lower limbs, see Figure 4.

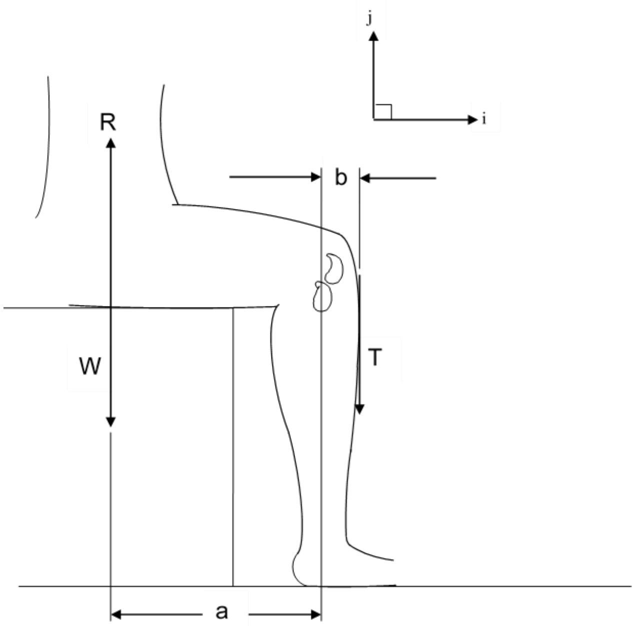

Figure 4: Patellar tendon at the sitting position (see also [17])

Using Eqn. (25) and with support from Hariri et al. [10], $\sum \vec{M}_o = 0$

$$\vec{a} \wedge \vec{W} + \vec{a} \wedge \vec{R} + \vec{b} \wedge \vec{T} = 0$$

$$- a\hat{i} \wedge - W\hat{j} + \left(- a\hat{i} \wedge R\hat{j}\right) + b\hat{i} \wedge - T\hat{j} = 0$$

$$aW\hat{k} - aR\hat{k} - bT\hat{k} = 0$$

$$\hat{k}: \quad T = \frac{aW - aR}{b} = \frac{a}{b}\left(W - R\right) \tag{36}$$

But from Eqn. (28), $\sum \vec{F} = 0$

$$W = mg = R$$

Therefore T = $\frac{a}{b}$ (mg – mg) = 0. Hence the patellar tendon force is f zero. We are left with the lumbar vertebra analysis which basically remains the same and we are left with:

$$\vec{F} = -\left(\frac{dkW + eL}{c}\right)\hat{j}\,N$$

$$\vec{R} = \left\{\frac{dkW + eL}{c} + kW + L\right\}\hat{j}\,N$$

$$\left.\begin{aligned} \left|\vec{F}_c\right| &= \left|\vec{R}\right|\cos\theta \\ \left|\vec{F}_s\right| &= \left|\vec{R}\right|\sin\theta \end{aligned}\right\} \qquad Rx\hat{i} = 0$$

In the sitting position, the radius and ulna are held a bit further from the torso than in the squat position. Thus, we obtain a configuration as seen in Figure 5. For equilibrium, Eqn. (25) holds

$$\sum \vec{M}_o = 0$$

$$\vec{h} \wedge \vec{T} + \left(h + f\right)\hat{i} \wedge \vec{W}_L + \vec{m} \wedge \vec{L} = 0$$

$$\vec{h} = h\hat{i}, \qquad \vec{m} = m\hat{i}$$

$$\vec{T} = T\left\{\frac{-h}{\sqrt{g^2 + h^2}}\hat{i} + \frac{g}{\sqrt{g^2 + h^2}}\hat{j}\right\}N$$

$$\vec{h} \wedge \hat{T}\frac{Tgh}{\sqrt{g^2 + h^2}}\hat{k}$$

So, we have:

$$\frac{Tgh}{\sqrt{g^2 + h^2}}\hat{k} - \left\{hW_L\hat{k} + fW_L\hat{k} + mL\hat{k}\right\} = 0$$

$$T = \frac{\sqrt{g^2 + h^2}}{gh}\hat{k} - \left\{hW_L + fW_L + mL\right\}N \tag{37}$$

Reaction at elbow joints,

Using Eqn. (28),

$$\sum \vec{F} = 0$$

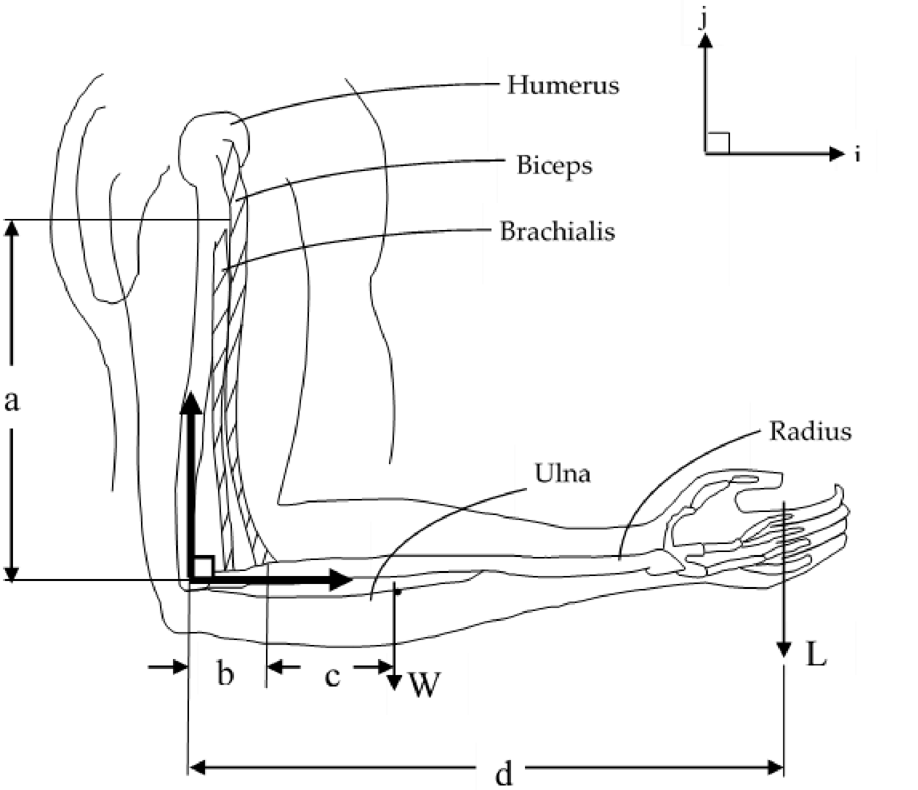

Figure 5: Radius and Ulna of human anatomy at sitting position (see also [17])

$$\vec{R} + \vec{T} + \vec{W}_L + \vec{L} = 0$$

$$Rx\hat{i} + Ry\hat{j} + -\left\{\frac{(h+f)W_L + mL}{g}\right\}\hat{i} + \left\{\frac{(h+f)W_L + mL}{h}\right\}\hat{j} - W_L\hat{j} - L\hat{j} = 0$$

$$\hat{i} \quad : \quad R_x = \frac{(h+f)W_L + mL}{g} \tag{38}$$

$$\hat{j} \quad : \quad R_y = WL + L - \left\{\frac{(h+f)W_L + mL}{h}\right\} \tag{39}$$

Bending

Here, we obtain maximum axial skeletal extension (Figure 6). The analysis proceeds as before but it is noteworthy that though dimension c remains constant, d and e have increased dramatically. L_5 is subjected to maximum shear.

Moreover, while engaging in the bending posture, there are several issues to avoid. Among these are anterior compression, posterior compression and uncontrolled inter-vertebral compression. Specifically, when embarking on the internal bending, the welder needs to avoid lateral compression. In the bending posture, there are specific important postures, which can be grouped as axial extension postures, difficult for the welding to hold are referred to as the downward dog.

$$\vec{F} = -\left(\frac{dkW + eL}{c}\right)\hat{i}\ N \tag{40}$$

Similar to Eqn. (32) but the values of d and e will increase. To obtain the compressive and shear forces on L^5, let $\vec{R}$ be the reaction at L_5 and $\vec{R} = Rx\hat{i} + Ry\hat{j}$,compressive force on L_5: $\left|\vec{F}_c\right|$ = R_x sin◎ + R_y sin◎ and shear force on L_5: $\left|\vec{F}_s\right|$ = R_x cos◎ + R_y sin◎, thus

$$\vec{R} + \vec{F} + \vec{W}u + \vec{L} = 0$$

$$\vec{R} = \left(\frac{dkW + eL}{c}\right)\hat{i} + kW\hat{j} + L\hat{j}$$

$$R_x = \frac{dkW + eL}{c}$$

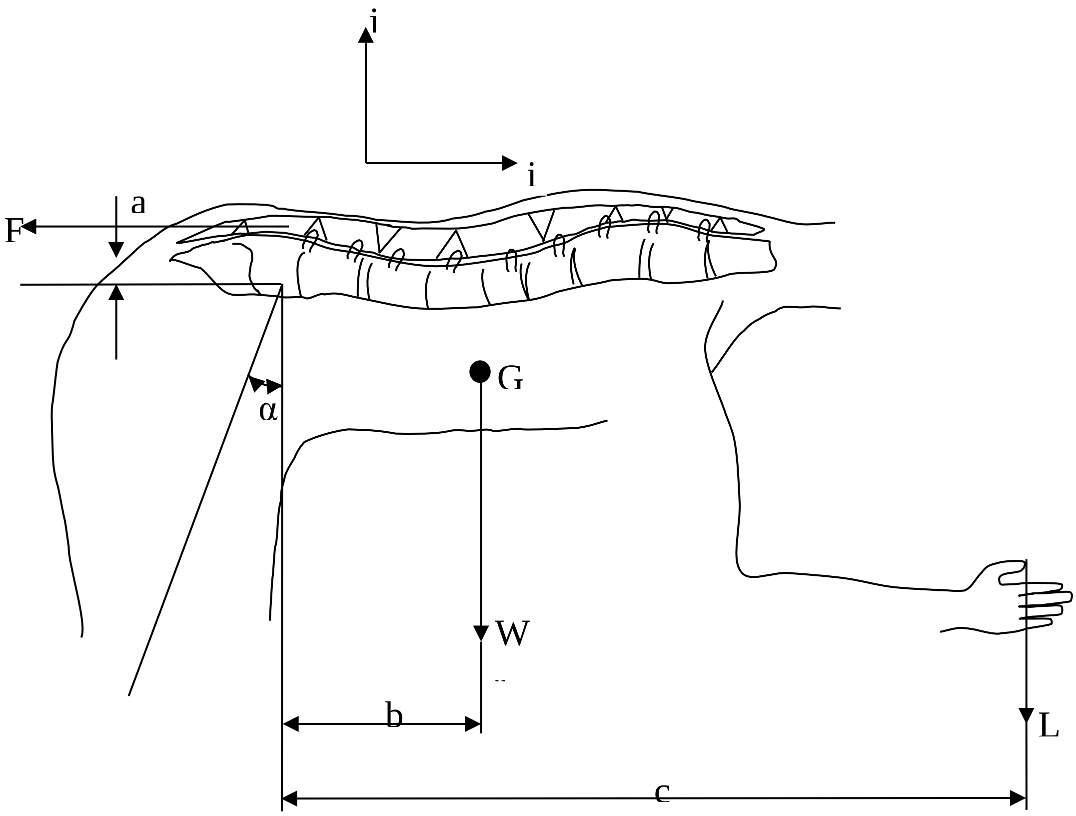

Figure 6: Anatomy of human while bending (see also [17])

$$R_y = kW + L$$

$$\vec{R} = \left(\frac{dkW + eL}{c}\right)\hat{i} + \left(kW + L\right)\hat{j} \tag{41}$$

$$\left|\vec{F}_c\right| = \left(\frac{dkW + eL}{c}\right)\sin\theta + \left(kW + L\right)\cos\theta \tag{42}$$

$$\left|\vec{F}_s\right| = \left(\frac{dkW + eL}{c}\right)\cos\theta + \left(kW + L\right)\sin\theta \tag{43}$$

Standing with arms stretched

Using Eqn. (25) $\sum \vec{M}_o = 0$ (Figure 7)

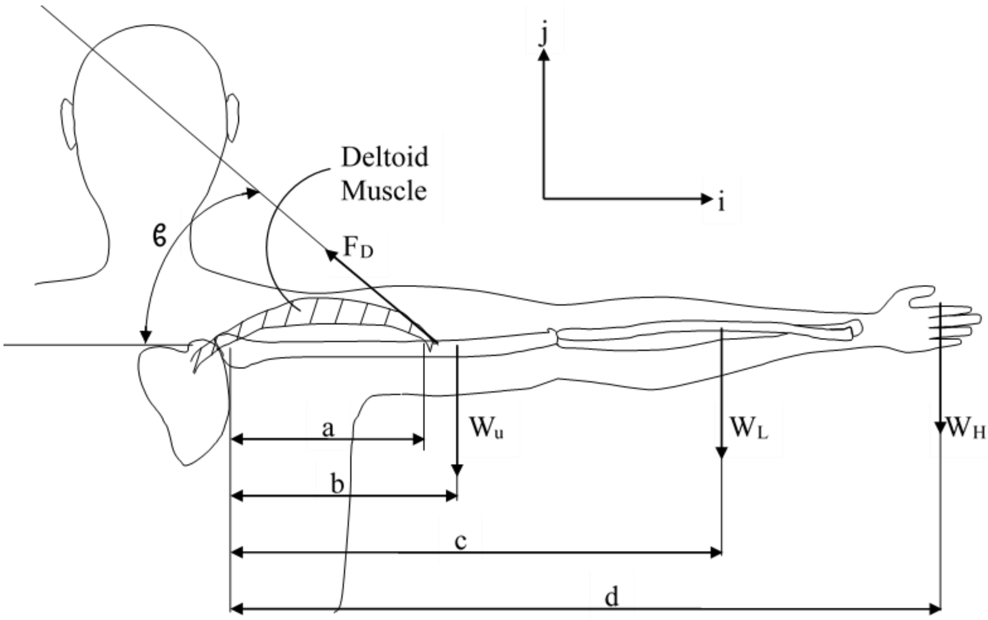

Figure 7: Anatomy of the human hand while standing with hand-stretched (see also [17])

Figure 7 shows a possible position of the stretching of the right hand of the welding while attempting to weld materials together. Although only the right hand is stretched while standing in Figure 7, the two hands may sometimes be stretched one after the other or concurrently, depending on the requirement of the welding task at that time. However, a discussion of the movement of the right hand alone and/or both the right hand of the welder is given in this section. The associated forces on the hands are shown in Figure 7. A further attempt is made to describe the movements of the muscles of the hands with the movement of the other parts of the welder's body remaining unmoved at that time. Also, coordination between the muscles of the welder's body and the bones is expected. To start with, the following details are given.

This discussion begins with the right hand stretched with a completely opened palm and the five fingers stretched without being wide apart. As the welding holds this position, it is possible to rotate the wrists in a clockwise direction. At this point, there is a coordination of the muscles with the joints of the hands. In performing welding tasks at this posture, the welders may open the hand and then press the arm long to properly position the welded material before applying the welding electrodes. In another situation, the welder may completely open the elbows to achieve picking fixing and welding the metal to the desired point. Moreover, in other situations, the welding may bend the wrists down while standing. The wrists could also be brought up. While still maintaining the standing position, the welder could stretch out the muscles such that they go up into the firearms. At the standing posture, the welder may also take a different hand posture by making a first and pressing it down. At this point, the elbows may start to bend and could be stretched out. The muscles that work the hands are felt at the firearms. An interesting position is to keep the wrist bent and at this point, the palms may be opened.

$$\vec{n} \wedge \vec{F}_D + \vec{p} \wedge \vec{W}_U + \vec{r} \wedge \vec{W}_L + \vec{s} \wedge \vec{W}_H = 0$$

$$n\hat{i} \wedge F_D \left(-\cos\gamma\hat{i} + \sin\gamma\hat{j}\right) + p\hat{i} \wedge -W_U\hat{j} + r\hat{i} \wedge W_L\hat{j} + s\hat{i} \wedge \vec{W}_H\hat{j} = 0$$

$$nF_D \sin\gamma\hat{k} - pW_U\hat{k} - rW_L\hat{k} - sW_H\hat{k} = 0$$

$$\hat{k}: \quad F_D = \frac{pW_U + rW_L + sW_H}{n\sin\gamma}$$

$$\vec{F}_D = \left\{\frac{pW_U + rW_L + sW_H}{n\sin\gamma}\right\}\left(-\cot\gamma\,\hat{i} + \hat{j}\right) \tag{44}$$

To obtain reactions at the shoulder joint, use Eqn. (28) [18], $\sum F = 0$

Let the reaction be $\vec{R} = Rx\hat{i} + Ry\hat{j}$

$$\vec{R} + \vec{F}_D + \vec{W}_U + \vec{W}_L + \vec{W}_H = 0$$

$$\vec{R} = Rx\hat{i} + Ry\hat{j}$$

$$\hat{i}: \quad Rx = \frac{\cot\gamma}{n}\left(pW_U + rW_L + sW_H\right) \tag{45}$$

$$\hat{j}: \quad Ry = W_U + W_L + W_H - \frac{\left(pW_U + rW_L + sW_H\right)}{n} \tag{46}$$

$$\vec{R} = \left(\frac{\cot\gamma}{n}\left(pW_U + rW_L + sW_H\right)\hat{i} + \left\{W_U + W_L + W_H - \frac{\left(pW_U + rW_L + sW_H\right)}{n}\right\}\hat{j}\right) N \tag{47}$$

Going back to Eqn. (24), the momentum term can be taken care of as follows: though the analysis has obtained equilibrium conditions, the muscles are constantly contracting and relaxing, expending energy as they do so. Hence from the principle of virtual work, if a force F moves through a distance ⊚x, it does work ⊚U.

$$⊚U = F⊚x \tag{48}$$

Taking muscle spasms at z m/s and time interval as ⊚t for a welding cycle, then modifying Eqn. (48),

$$\sum \delta U = F.z.\,⊚t \tag{49}$$

Energy expenditure due to the momentum term,

$$\frac{p^2}{2m} = Fz◎t \tag{50}$$

Taking z constant for all muscle groups and $\vec{F}$ as the vectorial sum of the relevant forces, Eqn. (24) can be rewritten as:

$$E = \frac{M_o V^2}{2} + K - \left(U_o + Fz\Delta z\right) + \frac{W^2}{2} I \tag{51}$$

To obtain I, we take the second moment of mass length ◎x about axis

$$X – x = ◎◎x ◎ x^2 \tag{52}$$

where ◎ = mass per unit length
and ◎x = sufficiently small such that x + ◎x ◎ x

Sum of all such masses:

$$I = \sum \rho x^2 \delta x \tag{53}$$

$$\text{where } ◎x ◎ 0\text{: } I = \int_0^L \rho x^2 dx = \frac{\rho L^3}{3} \tag{54}$$

But M = ◎L: Therefore,

$$I = \frac{M L_f^2}{3} \tag{55}$$

Now Eqn. (11) can be fully used to obtain the energy expenditure of a welder in a complete welding cycle. Then for a complete welding job, it is simply the sum of welding cycles.

$$E_{wj} = \sum_{k=1}^{n} E_{wc_K} \tag{56}$$

Combining Equation (11) and (51):

$$W = \frac{M_o V^2}{2} + K - \left(U_o + Fz\Delta t\right) + \frac{W^2}{2} I \text{ - } \left(\sigma \varepsilon A T^4 \Delta t + Lms\right)$$

where W is the energy expenditure. (U_o + Fz◎t) varies with the posture

Standing position occurs with the whole body balanced and stabilized while being aligned with the feet. In this situation, a small base support is needed by the muscles that work in coordination. Studies have advised the addition of some hours of standing position by workers limits the risk of diabetes, obesity and cardiovascular disease. A standing posture is maintained by keeping the neck tall and the shoulders relaxed [10]. However, is often suggested to keep a small footrest at one foot of elevation as the workers alternate positions to keep away from fatigue. It is often a caution not to slouch forward nor strain the spine through learning backwards in a standing position [10]. Moreover, in the workplace, the standing position is also encouraged to assist in enhancing posture since it motivates an upright position standing has been suggested as a position that enhances energy levels while assisting the welder to maintain focus while welding [3, 5, 7, 9].

3.0 CASE STUDY

A small welding workstation is considered, where the only source of labor is man. The desired equations are used to obtain real-time values for energy expenditure, given typical human anatomy dimensions: M_o = 0.5kg, U = 0.05m/s

K ◎ 0 (the welder at rest except for his forearm taken care of by the $\frac{M_o V^2}{2}$ & $\frac{Iw^2}{2}$ terms).

Internal muscular movements are taken care of by Fz◎t term. Note that I = $\frac{ML_f^{\,2}}{3}$

M = 3 kg, L_f = 30 cm = 0.3 m, Therefore I = $\frac{3 \times 0.3^2}{3}$ = 0.09 kgm²

w = 0.16 rad/s since 0 = wr,

U_o: Position in the gravitational field
The floor of the workshop is taken as the datum, hence the higher the center of gravity above the datum, the higher the work it is capable of achieving.

$$U_o = hW = \begin{cases} (0.5\ W)\ J\ \text{squatting} \\ (0.8\ W)\ J\ \text{sitting} \\ (1.0\ W)\ J\ \text{bending} \\ (1.4\ W)\ J\ \text{standing} \end{cases} \quad (57)$$

where W = mg the welder's weight, Z = 0.005 m/s, ◎t = 1200 sec [A 20 min cycle], ◎ = 5.6703 x 10^{-8}w/m²K⁴, ◎ = 0.7

To progress with the evaluation of the force associated with squatting when the patellar tendon, a muscle on the legs is considered, the complexion of the welder is first assumed. Undoubtedly, the natural complexions of welders are varied and it will determine the sweat that evaporates from the body of the welder during welding tasks. It is noted that a dark-skinned welder absorbs heat faster than a light-complex welder. Thus, it is assumed that a dark-complexed welder is used for the computation. Hence, the temperature of the body of the welder is first noted as being a little below 37°C, such as 35°C. Thus, the surface skin temperature of the welder is given as T = 35 + 273 = 308K. Also, L is given as 2256 kJ/kg. Now, assuming that the welder works for 200 minutes and an equivalent volume of 10ml of sweat evaporates from the welder. It implies that 1ml of sweat is given out by the welder in a 20-minute cycle of operations. If the density of the welder is taken as e' 1000 kg/m³, it implies that given 10 ml of sweat to be equal to 10^{-5}m³, the mass of the welder's sweat, eV is obtained as 1000 (10-5), which gives 0.001kg of sweat produced by the welder in 20 minutes. Now, assuming an average welder weighs 69kg which is 680N, to obtain the different values of $\vec{F}$ for the squatting patellar tendon force, Equation (27) is deployed where the values of a, b, ◎, ◎ are used, notably,

a = 30 cm = 0.3 m, b = 2 cm = 0.02 m, ◎ = 80°, ◎ = 85°

By substituting these independent terms into equation (27),

$$\vec{T} = \frac{0.3 \times 680}{2 \times 0.02}\left(\cos 85^{o}\,\hat{i} + \sin 85^{o}\,\hat{j}\right)N = \left(440\,\hat{i} + 5080\,\hat{j}\right)N$$, which yields $\left|\vec{T}\right| = 5100N$.

Lumbar Section

The examination of the force that the rectus muscle experiences due to the welding work is made in this section. To evaluate this force, specific values of K, Wu, c, d, e and L are required. Based on the researcher's experience and for illustration purposes, the following values of the desired parameters are used:

K = 65% = 0.65, Wu = 0.65 x 680 = 442 N, c = 50 mm = 0.05m, d = 30 mm = 0.03 m, e = 300 mm = 0.3 m, L = 3 x 9.81 = 29 N

However, it should be noted that earlier in the work, Equation (32) had expressed the force experienced by the rectus muscle, which is recalled for usage here. By substituting these values in the force Equation (32), the rectus muscle for force is obtained as

$$F = -\left(\frac{0.03 \times 0.65 \times 680 + 0.3 \times 29}{0.05}\right)\hat{j}\,N$$

Here, rectus muscle force: $\vec{F} = -\,440\hat{j}N$ $\left|\vec{F}\right|\ 440N$

Furthermore, in this article, sitting is one of the postures analyzed in the modeling section with the final expression represented in Equation (37) [20]. However, to appreciate what the values of the force associated with the sitting posture is subjected to, numerical values need to be substituted into Equation (37). These values are given as

m = 30 cm = 0.3 m, h = 5 cm = 0.05 m, f = 10 cm = 0.10 m, g = 20 cm = 0.20 m, W_L = 3 ◎ 9.81 = 29 N and L = 3 ◎ 9.81 = 29 N

Now, substituting these numerical values into equation (37),

$$T = \frac{\sqrt{0.2^2 + 0.05^2}}{2 \times 0.05}\left\{\left(0.05 + 0.1\right)29 + 0.3 \times 29\right\} = 269N$$

and $\vec{T} = \left(-\,65\,\hat{i} + 260\,\hat{j}\right)N$

Next is the bending posture that the welder is subjected to [19], which utilizes Equation (40) to evaluate the final force emerging from the substitution of the independent variables into Equation (40). These independent variables are as follows:

c = 50 mm = 0.05 m, d = 150 mm = 0.15 m, e = 1000 mm = 1 m

The results of the evaluation are given as;

From Eqn. (40), $\vec{F} = -\left(\frac{0.15 \times 0.65 \times 680 + 1 \times 29}{0.05}\right)\hat{i}\,N = -1906\,\hat{i}\,N = 1906N$

Standing

N = 0.15 m	◎ = 40°	P = 0.16 m	Wu = 4.5 ◎ 9.81 = 441 N
R = 0.3 m	W_L = 3 ◎ 9.81 = 29 N	S = 0.45 m	W_H = 3 ◎ 9.81 = 29 N

$$\text{From Eqn. (44), } F_D = \frac{0.16\times 44 + 0.3\times 29 + 0.45\times 29}{0.15\sin 40} = 300 \text{ N}$$

$$\vec{F}_D = \left(-230\,\hat{i} + 193\,\hat{j}\right)\text{N}$$

Using Eqn. (57), Eqn. (57) is separated into 3 parts:

$$\text{Part 1: } \left(\frac{M_oV^2}{2} + \frac{Iw^2}{2}\right) \text{ Assumed the same for all postures.}$$

$$\frac{0.5\times 0.052}{2} + \frac{0.16^2}{2} \times \frac{3\times 0.3^2}{3} = 1.78 ◎ 10^{-3}\text{J}$$

Part 2: PK terms

$$H_{sweat} + H_{radiated}$$

Also assumed to remain the same for all postures

= - (5.6703 ◎ 10^{-8} ◎ 0.7 ◎ 2.7 ◎ 308^4 + 2256000 ◎ 0.001) = - (964.4 + 2256) = -3.22 kJ

Part 3: (U_o + Fz◎t) terms

This is the sole determinant for posture energy expenditure as it gives the relative position in the gravitational field as well as muscle energy expenditure.

Squatting: -(U_o + Fz◎t) = - (0.8 ◎ 689 + (269 + 440) 0.05 ◎ 1200) = -4.8 kJ

Bending: - (U_o + Fz◎t) = - (1.0 ◎ 680 + 1906 ◎ 0.05 ◎ 1200) = 12.1 kJ

Standing: - (U_o + Fz◎t) = - (1.4 ◎ 680 + 300 ◎ 0.05 ◎ 1200) = -2.75 kJ

Table 1: Total Energy Expenditure

	$\frac{M_oV^2}{2} + \frac{Iw^2}{2}$	P_K (kJ)	(U_o + Fz◎t)	Total
Squatting	negligible	-3.22	-33.6	-36.8
Sitting	negligible	-3.22	-4.8	-8.02
Bending	negligible	-3.22	-12.1	-15.32
Standing	negligible	-3.22	-2.75	-5.97

From Eqn. (56), if we assume that each welding cycle is identical then it is possible to estimate the total number of cycles for a complete welding job and then obtain the total energy expenditure for a working day. This can then be compared to the calorific requirements for individual persons.

4.0 CONCLUSIONS

Insight has been gained on energy expenditure from the point of view of thermodynamics with the aid of engineering mechanics used to analyze the human anatomy. It was seen that squatting is the worst way to undertake welding from an energy expenditure point of view. No attempt has been made to include the intricate details of welding which may or may not approve of squatting for a particular kind of welding job. It was surprising that standing used less energy than sitting. Primarily, this was due to the reduced stresses on the lower back when no heavy load is carried while standing. Also, when sitting, the lower back was not supported as assumed in this analysis. All other things being equal, it is recommended that welders choose the following postures: (i) Standing, (ii) Sitting (iii) Bending (not advised for long periods), (iv) Squatting (not advised for long periods). The force analysis may be used in determining equilibrium conditions in human-like robotic systems of the not-too-distant future.

Notations

E	Internal energy of the welder
P_k	heat transfer due to the body radiation and perspiration
T	surface skin temperature of the human body (in kelvin)
◎	Stefan-Boltzmann constant
◎	emissivity of skin surface
A	surface area of skin (m2)
◎t	time interval(s)
H_{sweat}	heat of transformation required to evaporate the perspiration (sweat)
L	energy per unit man required to vaporize sweat
m_s	mass of sweat (kg)
K	kinetic energy
U	potential energy
p	momentum
◎	angle between the lower limb and the vertical
O	point at which the femur meets the tibia and is taken as the origin of the frame of reference
b	perpendicular distance between the line of action of the patellar tendon force and the origin O.
a	perpendicular distance between the welder's toes at the ground and the vertical line through the origin.
◎	5.6703 x 10^{-8}W/m^{2}K^4 Stefan-Boltzmann constant
◎	emissivity of skin surface (For an African (black-skinned) welder it will be closer to 1, for a Caucasian (light skinned) welder it will be closer to zero, 0).
A	surface area of skin (m^2)
T	surface skin temperature (in Kelvin)
◎t	time interval (s)
dh	change in enthalpy
c_p	specific heat capacity at constant pressure
dT	change in temperature (absolute)
$\sum \delta Q$	net heat transfer between the welder and his surroundings and
$\sum \delta W$	net work transfer
M_0	mass of welding rod and other moving parts carried
v	linear speed of weld
K	kinetic energy of welder (usually negligible since welder is static)
U_0	gravitational potential energy initially in welder
$\frac{p^2}{2m}$	momentum component of the welder's energy and can be obtained from the forces

I moment of inertia of any rotating part of the welder, usually his forearm which transverses an angular path when welding
◎ angular speed of such movement as above
c distance between the line of action of reactus muscle force to L_5
d distance between center of gravity of the upper torso to L_5
e displacement of force load from L_5
◎ angle of declination of L_5 to the horizontal
M mass of the forearm
L_f length of the forearm
n point of attachment of deltoid muscle from shoulder joint to humerus.
p distance of c. of gravity (from shoulder joint) of the upper arm
r distance of c. of g of forearm (from shoulder joint)
s approximate length of the fully stretched arm carrying load W_H

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