

OCCUPATIONAL BIOMECHANICAL DEMAND EVALUATION

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ABSTRACT

Humans are ill adapted to industrial tasks. Quantification of loads is essential to improve the control of musculoskeletal injuries in occupational settings. To this end, a strategy to quantify loads due to posture, motion, force, and repetition is being proposed. Joint positioning in excess of neutral posture during an industrial activity can be depicted as percentage increase in postural load. A similar treatment of motion as a percent of range of motion will define the motion related load (the sum of the percentages of angular motions in relation to the ranges of motion of each joint, divided by the number of joints taken into account). Similarly, force can be represented as a percent of the strength of the body segment, and repetition can be quantified as a percent of possible repetition. A collective derivative of these values will begin to quantify the total demand on individuals. Finally, human physiology and biomechanics-based elemental behavior and tolerance databases will need to be developed against which the industrial load could be compared to assess safety. A strategy of optimizing macro and micro components of ergonomics for optimal productivity and safety needs to incorporate the variables that determine work-related physical exertion. If followed, the proposed system may add new information that will contribute to a better understanding of the working physical demands and its relationship with musculoskeletal injuries.

INTRODUCTION

Biomechanical hazards, genetic predisposition, morphological disadvantages, and psychosocial propensity all interact in the precipitation of work-related musculoskeletal disorders (Kumar, 2001). The U.S. Department of Labor defines musculoskeletal disorders as “an injury or disorder of the muscles, nerves, tendons, joints, cartilage, and spinal discs” (BLS, 2001). According to the U.S. Bureau of Labor Statistics, work-related musculoskeletal disorders include sprains, strains, tears, soreness, pain, carpal tunnel syndrome, hernias, and connective tissue injuries that were caused by reactions of the body during work such as overexertion and repetition on bending, climbing, crawling, reaching, and twisting (BLS, 2001). Awkward, constrained, asymmetric, repeated, and prolonged postures; overstressing movements, high repetition; and force can overload the tissues and exceed their threshold of tolerable stress, causing injury due to overexertion or imbalance (Kumar, 2001). The physical exertion determinants need to be considered altogether in order to categorize and analyze the physical demands of the work (Armstrong, 1986; Kumar, 1994; Westgaard, 1997; Magnusson, 1998; Coury, 1999).

The maintenance of static postures and force exertion for prolonged periods of time compresses the veins and capillaries inside the muscles, causing micro lesions (microscopic injuries) due to the absence of tissue oxygenation and nutrition (Kumar, 1990; Kumar, 1994). These factors can cause fatigue, discomfort, and disruption of tissues activating the nociceptors, and, as a result, the worker experiences pain and may begin to exhibit pain behavior such as kinesiophobia (fear of moving), resulting in prolonged dysfunction. The tissues that are injured due to overexertion are the muscles, their tendons, and the ligaments. Nerves can be injured secondarily due to compression or ischemia. In addition, the joints' bones and their cartilages can also be damaged by the load and strain accumulated over years of activity (Kumar 2001; Armstrong, 1993; Buckle, 2002).

Musculoskeletal health can be maintained by controlling for risk factors, but it is only feasible to control for the biomechanical and, to a lower extent, psychosocial risks. Since the industrial revolution, many risks to the development and aggravation of musculoskeletal disorders have been identified and controlled to some extent. The methods currently in use to evaluate work physical demands are the Ovaco Working Postures Assessment System - OWAS (Karhu, 1977), the Rapid Upper Limb Assessment - RULA (McAttamney, 1993), and the Rapid Entire Body Assessment - REBA (Hignett, 2000). These methods use on-the-job observation or video recordings to categorize the ranges within which each body segment falls and the estimated loads handled. Also, direct measures such as goniometers, inclinometers, photographic techniques, electrogoniometers, and video recording systems are used to measure working postures, movements, and repetition. In addition, dynamometers are used to measure the force exerted during a job task, and electromyography is used to record the electric activity of some of the muscles contracting during work exertion.

Independently of the recording method used, a classification system of the risk associated with work biomechanical demands is necessary. By classifying and quantifying the details of the different physical exertions at work one might be able to know the position that maximizes biomechanical advantage of muscles and the safe ranges that work can be done with reduced risk. Thus, a quantitative classification system of the physical exertion determinants (energy consumption, posture, movement, and force) would allow a better control for work-related musculoskeletal injuries and disorders. For this reason, the objective of this paper was to develop and propose a system to quantitatively evaluate the work biomechanical demands. For conciseness, the present paper presents the proposed system using the movement dimension of work physical exertion as an example.

METHODS

Based on the need of an evaluation system for the work biomechanical demands, a literature review was conducted focusing mainly on studies measuring working postures and movements, and on studies concerning the measurement devices' reliability and validity (Vieira, 2004). Based on the information gathered in the review, the present system of evaluation was developed and an initial report was presented (Vieira, 2003).

The process followed in identifying the most appropriate evaluation system for the movement dimension was based on the range of motion, joints positioning, and angular motion covered during work. For each preliminary model developed, trials were conducted so that data from simulated work activities were entered in the models and checked in relation to their appropriate classification. The content and usefulness of the system was further considered and elaborated resulting in modifications of the initial idea and the final model is presented in this paper.

RESULTS

The movement dimension demand of the work physical exertion can be classified according to the movement demand index (MDI). The MDI is expressed as angular motions in relation to the ranges of motion of each joint, divided by the number of joints taken into account (Equation 1).

Calculation of the Movement Demand Index (MDI):

$$MDI = \frac{100}{n} \sum_{j=1}^n \frac{AM_j}{ROM_j} \quad (1)$$

Where, j = Joints 1...n, n = accounted number of joints, AM = Angular Motion, ROM = Range of Motion. ROM is the maximum range that a joint can actively cover and AM is the range that a joint covers during an activity.

This calculation results in a mean MDI, which is used to estimate an overall evaluation of the movement dimension work demand. The steps needed to get to the overall MDI provide information about the specific joints (head/neck, trunk, two shoulders, two elbows, two wrists, two hips, two knees, and two ankles) and body regions (head/neck and trunk, upper limbs, and lower limbs). Thus, this system gives the MDI of each joint and each body region, as well as the overall MDI (Tables 1 to 4).

Table 1. Head/neck and trunk (hnt) movement demand evaluation table: range of motion (ROM), angular motion (AM), joints (j), and movement demand index (MDI).

| JOINT | ROM ^o | AM ^o | MDI _j |
|-------------------------|---------------------------------------|--------------------------------------|---------------------------|
| Head/neck* | | | |
| Flexion | 65 | | |
| Extension | 50 | | |
| Left Lateral Flexion | 57 | | |
| Right Lateral Flexion | 57 | | |
| Left Rotation | 94 | | |
| Right Rotation | 94 | | |
| Trunk** | | | |
| Flexion | 85 | | |
| Extension | 30 | | |
| Left Lateral Flexion | 28 | | |
| Right Lateral Flexion | 28 | | |
| Left Rotation | 38 | | |
| Right Rotation | 38 | | |
| Occupation/Task: | ROM_{hnt}^o: | AM_{hnt}^o: | MDI_{hnt}: |

*Mean ROM values from Nordin, 1989. **Mean ROM values from AAOS, 1965.

Table 2. Upper limbs (ul) movement demand evaluation table: range of motion (ROM), angular motion (AM), joints (j), and movement demand index (MDI).

| JOINT | ROM° | AM° | MDI_j |
|-------------------------|---------------------------|--------------------------|--------------------------|
| Left Shoulder | | | |
| Flexion | 188 | | |
| Extension | 61 | | |
| Abduction | 134 | | |
| Adduction | 48 | | |
| Lateral Rotation | 34 | | |
| Medial Rotation | 97 | | |
| Right Shoulder | | | |
| Flexion | 188 | | |
| Extension | 61 | | |
| Abduction | 134 | | |
| Adduction | 48 | | |
| Lateral Rotation | 34 | | |
| Medial Rotation | 97 | | |
| Left Elbow* | | | |
| Flexion | 52 | | |
| Extension | 90 | | |
| Right Elbow* | | | |
| Flexion | 52 | | |
| Extension | 90 | | |
| Left Wrist | | | |
| Flexion | 90 | | |
| Extension | 99 | | |
| Ulnar Deviation | 27 | | |
| Radial Deviation | 47 | | |
| Right Wrist | | | |
| Flexion | 90 | | |
| Extension | 99 | | |
| Ulnar Deviation | 27 | | |
| Radial Deviation | 47 | | |
| Occupation/Task: | ROM_{ul}°: | AM_{ul}°: | MDI_{ul}: |
| | | | |

Mean ROM values from Chaffin, 1991.

*Neutral position = 90° between upper and lower arm.

Table 3. Lower limbs (ll) movement demand evaluation table (A = if not sitting, B = if sitting): range of motion (ROM), angular motion (AM), joints (j), and movement demand index (MDI).

A

| JOINT | | ROM° | AM° | MDI _j |
|-------------------------|-----------------|---------------------------|--------------------------|--------------------------|
| Left Hip | Flexion | 113 | | |
| | Abduction | 53 | | |
| | Adduction | 31 | | |
| Right Hip | Flexion | 113 | | |
| | Abduction | 53 | | |
| | Adduction | 31 | | |
| Left Knee | Flexion | 159 | | |
| Right Knee | Flexion | 159 | | |
| Left Ankle | Dorsi-Flexion | 35 | | |
| | Plantar-Flexion | 38 | | |
| Right Ankle | Dorsi-Flexion | 35 | | |
| | Plantar-Flexion | 38 | | |
| | Flexion | 52 | | |
| | Extension | 90 | | |
| Occupation/Task: | | ROM_{ll}°: | AM_{ll}°: | MDI_{ll}: |
| | | | | |

Mean ROM values from Chaffin, 1991.

B

| JOINT | | ROM° | AM° | PRI _j |
|-------------------------|-----------------|---------------------------|--------------------------|--------------------------|
| Left Hip* | Flexion | 23 | | |
| | Extension | 90 | | |
| | Abduction | 53 | | |
| | Adduction | 31 | | |
| Right Hip* | Flexion | 23 | | |
| | Extension | 90 | | |
| | Abduction | 53 | | |
| | Adduction | 31 | | |
| Left Knee** | Flexion | 69 | | |
| | Extension | 90 | | |
| Right Knee** | Flexion | 69 | | |
| | Extension | 90 | | |
| Left Ankle | Dorsi-Flexion | 35 | | |
| | Plantar-Flexion | 38 | | |
| Right Ankle | Dorsi-Flexion | 35 | | |
| | Plantar-Flexion | 38 | | |
| Occupation/Task: | | ROM_{ll}°: | AM_{ll}°: | PRI_{ll}: |
| | | | | |

Mean ROM values from Chaffin, 1991.

*Neutral position = 90° between the trunk and the thigh. **Neutral position = 90° between thigh and lower leg.

Table 4. Overall movement demand evaluation table: movement demand index (MDI).

| Body Region | MDI (%) |
|---------------------------|---------|
| Head/neck and trunk | |
| Upper limbs | |
| Lower limbs (not sitting) | |
| Lower limbs (sitting) | |
| OVERALL | |

A similar processing of the other relevant variables (energy consumption, force, repetition, and duration) will give a broader representation of the work biomechanical demands, and thus should be conducted.

DISCUSSION

A successful ergonomic intervention could result in better control of work-related musculoskeletal disorders. To achieve this major goal of ergonomics, the work physical exertion has to be better understood and the risks need to be systematically classified in a precise and comprehensive manner. The system proposed here might be a first step in this direction. It helps to understand work physical exertion and can be used as a common approach for biomechanical load evaluation. The outcomes of the presented example classify the movement dimension risk of fourteen joints (head/neck, trunk, two shoulders, two elbows, two wrists, two hips, two knees, and two ankles), three main body regions (head/neck and trunk, the upper limbs, the lower limbs), and the overall risk. The use of the system proposed here will show where the physical ergonomic intervention is needed and can also be used to assess the degree of success of the movement dimension load-guided intervention.

The angular motion and position involved in any task influence the amount of force that the worker is able to generate. A possible categorization of the range of motion and position is: (1) within optimal mechanical advantage - within 20% of the neutral position of the joint (Kumar, 1994); (2) outside the optimal mechanical advantage range - >20% of the neutral position of the joint. These parameters can be used to evaluate the angular motion of each joint, showing which joints are most exposed and possibly at risk. Specifically for the shoulder and back, Punnett, Fine, and Keyserling (1987) found a mean odds ratio (OR) of 4.28 for those workers whose AM during work exceed 34% of the ROM.

According to Chaffin (1973) the moment and required muscle force increases 50% when the neck is flexed at 30° (approximately 50% of ROM). Also, the endurance time is significantly reduced at neck flexion $\geq 30^\circ$. Localized fatigue develops with uninterrupted contraction and is associated with localized muscle pain. Neumann *et al.* (2001) studied the relation between physical exposure and low-back pain. Posture and load samples were recorded during the work-shift on a paper using categorical scales. It was found that low-back pain is associated with

maximum flexion angle (OR = 2.2), peak spinal loads (OR = 2.0), average spinal loading (OR = 1.7), percent of time with loads in the hands (OR = 1.5), and percent of time spent in flexion > 45° (OR = 1.3) (approximately 50% of ROM as well). In relation to the shoulder joint, Bjelle, Hagberg and Michaelsson (1979) found that close to 70% of the patients of an occupational health clinic with shoulder pain worked with hands at or above shoulder level. Also, Hagberg and Wegman (1987) found an odds ratio (OR) to rotator cuff tendonitis of 11 when working with hands at shoulder level in comparison to work below this level.

The duration and repetition of the physical exertion has a cumulative effect on the musculoskeletal system (Kumar, 1990). Exertion duration should be taken into account in order to establish work-rest schedules (frequency and duration of the breaks). The proposed system can be applied using sampling techniques or continuous measurement to evaluate the total duration of the work. For jobs characterized by short cycles, direct measures can be taken for the entire cycle and the job does not necessarily need to be broken down into tasks, nor are sampling techniques necessary. For jobs with long cycles, there are still direct measures that can be taken but the job may have to be decomposed into tasks, and those have to be weighted based on the percentage of duration of cycle.

The system proposed here allows flexibility in relation to which methods will be used to collect the biomechanical data and in relation to the number of joints or body regions that will be taken into account. In studies dealing with work-related musculoskeletal disorders, quantitative measures are needed for physical workload assessments. In addition, the effect of ergonomic interventions can be directly evaluated using devices. High repetitiveness (.53Hz) was found to be directly associated with neck and upper limb disorders; prevalence of 56% on the left hand of female workers (age-adjusted prevalence odds ratio = 3.5) when compared to low repetitive work (.28Hz, prevalence of 26%) (Hansson, 2000).

A combination of an automatic videometry with flexible electrogoniometers seems to be the most suitable method of recording the body postures/movements in order to use the proposed classification system. Even in situations that do not allow the use of hard tools to directly measure body kinematics, observer based protocols can be used; these protocols are often used in field studies. The method proposed here can improve the evaluation of the postural load in both types of assessment (direct and observer based measures).

A general assessment of the body posture is ideal for a more complete evaluation. In situations where a full recording is not feasible, even the regional assessment of the body region(s) most at risk during the work can add valuable information. This type of regional assessment is also allowed by the proposed system. If the task involves the use of only one limb (e.g. use of only the right upper limb to operate a wheel) then the MDI value for that region can be calculated as well.

CONCLUSIONS

Prolonged and repeated exertions produce harmful physical exposure that can cause musculoskeletal injury, pain, and kinematic disorders. The movement dimension risk can be classified, among other things, according to the percentage of angular motion in relation to the

range of motion. The proposed classification system may contribute to a better understanding of the relationship between physical exertion and work-related musculoskeletal illness. Hopefully, it will provide a common approach for occupational biomechanical demand evaluation and help to improve the control of the highly prevalent work-related musculoskeletal disorders.

SUGGESTIONS FOR FURTHER RESEARCH

Additional categories of factors involved in the determination of physical demands of work can be introduced in order to include other relevant variables, but further studies are necessary to enable the establishment of the appropriate levels and multipliers. Human physiology and biomechanics based elemental behavior and tolerance databases need to be developed against which the industrial load can be compared to assess safety.

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