Review Article

Abating Biomechanical Risks: A Comparative Review of Ergonomic Assessment Tools

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ABSTRACT

Ergonomic assessment tools are crucial for evaluation of biomechanical risk factors at workplaces to understand the contributing factors and reduce the prevalence of musculoskeletal disorders (MSDs) which have negative implications on employees' health and productivity. This review examines a range of methods and ergonomic assessment tools. It shows ergonomic assessment tools, particularly postural analysis to comprise self-reports from workers, observation method, direct measurement method and advanced techniques for assessment of postural change in executing highly dynamic activities. These tools have been designed for different work activities consisting typically of manual handing, repetitive tasks and static loading. Some of the tools target at specific body parts while others at multiple body parts. The tools have the strengths particularly in the assessment of recurring tasks in standing or sitting postures involving specific or multiple body parts. However, the tools also have obvious limitations in terms of not considering vibration, contact stress and trauma to other body parts for tools assessing specific body parts, and undifferentiated weight of different ergonomic risks for whole-body tools. These strengths and shortcomings prompt a user to consider the job nature and tasks to be assessed prior to selecting the tools. This review advocates an integrated approach in ergonomic assessment using a combination of general and specific methods with direct measurements if permissible. It contributes to the accurate selection of the postural analysis tools through systematically presenting their features and limitations besides highlighting improvement of methods and approaches in ergonomic assessment.

Keywords: Assessment, biomechanical, ergonomic, musculoskeletal disorders, psychosocial

1. INTRODUCTION

Ergonomic risk factors are potential situations where the principles of ergonomics are compromised leading to adverse occupational or non-occupational health consequences of workers or users of items (1). Understanding ergonomic risk factors at workplaces is essential in preventing ergonomics-related illnesses such as musculoskeletal disorders (MSDs) (2). Ergonomic risk factors are closely related to the occupational environment consisting of two major elements i.e. the psychosocial and the physical aspects. An individual's interactions with the occupational environment generate mutual influence between the work environment and his/ her well-being which impacts productivity of the individual at work (3).

Physical attributes such as noise, vibration, light, temperature and radiation are associated with the physical aspect of an occupational environment while psychosocial aspect is related to the way work is organized, designed and managed (4). Psychosocial aspect centers on issues such as work demands, control at work, social relationship and reward system (4). Both aspects of the occupational environment give rise to three ergonomic risk factors, i.e. biomechanical exposures, psychosocial stressors and individual risk factors. Biomechanical exposures are linked to poor workplace designs, repetitive motion, high forces and deviation from neutral body alignment (5). Psychosocial stressors are concerned with high perceived occupational stress, low perceived social support, low perceived job control and time pressure (6).

The common ergonomic risk factors as a result of biomechanical exposures are repetition, force, vibration, contact stress, static loading and extreme temperature (4)(5). These ergonomic risks could lead to MSDs in the long run. MSDs have been regarded as the major contributor to disability globally and low back pain is particularly the most important cause of such disability. Approximately 20% to 33% of the global population suffer from MSDs and it was not limited to the elderly. MSDs significantly affect the ability of a person to work by limiting mobility and dexterity, thus, affecting the ability to generate incomes and participate in social activities. MSDs are also the main reason for the loss of productivity at workplaces and accounted for USD 213 billion of economic loss equivalent to 1.4% of the US gross domestic product in 2011 (7) .

With the significant health and economic implications of MSDs and biomechanical or ergonomic factors as a major contributor to occupational MSDs, this review aims to examine how biomechanical factors at work contribute to the development of MSDs and critically compare the various methods and tools used for ergonomic assessment. It is expected to provide new insight and useful information in the selection of methods and tools to more effectively assess the ergonomic risk factors at workplaces.

In this review, a literature search was conducted with online databases comprising ProQuest, Web of Science and Scopus using keywords such as ergonomic assessment, ergonomic tools, biomechanical factors, ergonomics, psychosocial, musculoskeletal disorders etc. The period of publication was not specified to gather all literature relevant to the genres of ergonomic or biomechanical factors in MSDs development as well as the methods and tools for ergonomic assessment. The titles and abstracts of the articles gathered were subsequently screened to select the most pertinent ones for this review. Articles selected for the review should fulfil the criteria of 1) addressing how biomechanical factors lead to the development of MSDs, 2) illustrating and reviewing the methods commonly employed in assessing ergonomic risks and 3) describing and comparing the tools for ergonomic assessments particularly the contents of assessments as well as their strengths and limitations.

2. BIOMECHANICAL FACTORS AND MUSCULOSKELETAL DISORDERS

MSDs are intricately related to biomechanics via a closed cybernetic model where muscle is the protagonist and launches actions upon the external loads in the work environment. The actions can be repetitive movements or lifting of heavy loads which produce muscular reactions affecting the tendons and the articulations through internal biochemical loading (8). This internal load will cause medium or long-term MSDs if it goes beyond the tolerance level of the biological tissue, leading to discomfort or pain (8). The musculoskeletal response is often directly proportional to the internal load exceedance which is quantifiable physically via direct measurement methods mentioned previously and observational methods such as the NIOSH Lifting equation (9).

Biomechanical risk factors such as articular postures, efforts, repetitive work, static posture and vibrations are subject to extensive studies, and it is known that the effects of biomechanical risk are influenced by the duration of exposure, the duration of recuperation and temperatures (10). These studies establish connection between the risk factors, especially their combined effects and the development of MSDs in the upper limbs (9)(11). While correlations have been drawn between the intensity of biomechanical risk factors at work and the risk of MSDs development, Lanfranchi and Duveau underscored the exception that certain tasks of low physiological demand such as working in front of computer and assembling electronic components actually led to considerable stress and mental load (6). These tasks have very low muscular demand but the development of MSDs in the shoulder associated with them is prevalent. Research into such tasks would require understanding of neurophysiology of motor units. In addition, development of MSDs is also subject to confounding variables such as healthy lifestyle which comprises, among others, the attributes of body mass index, gender and physical exercise (12)(13).

While there are multiple factors complicating the development of MSDs, an understanding of physical work factors is crucial in identification of the biomechanical risk factors. The physical work factors refer to interaction between the workers and the work setting, and comprise posture, force, velocity/ acceleration, repetition, duration, recovery time, heavy dynamic exertion and segmental vibration (8). Awkward posture increases physical demand of work by increasing the exertion requirement of smaller muscle groups while decreasing the ability of larger and stronger muscle groups to perform at maximum capacity. This impairs blood flow and increases the rate of fatigue (14). Awkward postures are characterized by repeated or prolonged reaching, twisting, bending, working overhead, kneeling, squatting and holding fixed positions or pinch grips. Repetitive motions and forceful exertions aggravate the effects of awkward postures. Awkward postures, in certain cases, are associated with visual effort, for instance handling or assembling small components which may lead to physical exertion and eye strain (10)(15).

Repetitive motions involve repeated use of same group of muscles, tendons or joints. Factors affecting the extent of repetition are the pace of work, the recovery time for muscles and the variety of work tasks performed. The pace of work can be machine controlled, for instance via working on production line, or administratively controlled via incentives or performance appraisal. MSDs, particularly of the hands, wrists, elbows and shoulders may result from highly repetitive jobs with low force exertions (9)(16).

Force is the amount of muscular effort required to perform a task. Exerting excessive force can result in fatigue and physical strain (15). Force is involved in lifting, lowering or carrying, pushing or pulling, and gripping. The amount of force exerted is affected by factors including the followings (6)(10)(17):

- Load shape, weight, dimensions and bulkiness.
- Grip type, position and friction characteristics.
- Amount of effort required to start and stop the load when moving it, i.e. how physically demanding it is to accelerate or decelerate the load.
- Length of time continuous force is applied by muscles, i.e. the duration a load or object is continuously held, carried or handled.
- Number of times the load is handled per hour or work shift.
- Amount of associated vibration.
- Body postures adopted.
- Resistance associated with moving the load.
- Duration of task over the work shift.
- Environmental temperature.

- Amount of rotational force, i.e. torque from tools or equipment.

Pressure points or contact stress are created when body is pressing against hard or sharp surfaces, for instance when resting wrist or elbow on sharp edge of a work surface and using hand tools with short handles that prod the hands. Body parts where nerves, tendons and blood vessels are in proximity with skin and underlying bones are particularly susceptible to contact stress. Examples of the body parts are fingers, palms, wrists and forearms, elbows and knees (15).

Exposure to continuous vibration of high intensity may result in fatigue, pain, numbness, tingling, increased sensitivity to cold and decreased sensitivity to touch in the fingers, hands and arms (18). Use of vibrating tools such as sanders, grinders, chippers, drill and circular saws expose the users to hand-arm vibration. Whole-body vibration commonly results from sitting or standing on work surfaces that vibrate, such as vibrating vehicles and platforms. Whole-body vibration contributes to general discomfort and lower back pain (19).

3. METHODS AND TOOLS USED FOR ERGONOMIC ASSESSMENT

With MSDs resulting from biomechanical risk factors becoming more prevalent and persistent at workplaces, various tools are used for the assessment of MSDs risk in order that appropriate solutions can be formulated and controls implemented. Postural analysis tools, for instance, are used to evaluate working posture related to manual handling and exposure to MSDs risk. They are classified into self-reports from workers, observation method, direct measurement method and advanced techniques for assessment of postural change in executing highly dynamic activities (1).

Self-reports from workers involve data collection via workers' diaries, interviews and questionnaires to identify the physical and psychosocial risk factors at the workplace. The use of Standardized Nordic Questionnaire is an example of such technique (1). The Standardized Nordic Musculoskeletal Questionnaire was developed to facilitate identification of ergonomic risks in the work environment, workstation and tool design via measuring the prevalence of MSDs. It is not intended as a tool of clinical diagnosis. Rather, it serves as a repeatable and useful screening and surveillance tool for the study of MSDs and ergonomic risk factors in the workplace (20). The questionnaire consists of two sections. Section 1 has a 40 forced-choice survey items to identify which of the nine body areas, i.e. neck, shoulders, upper back, elbows, low back, wrist/ hands, hips/ thighs, knees and ankles/ feet, show symptoms of MSDs in the last 12 months and last 7 days sufficiently severe to prevent normal activity. A body map indicating the nine body areas is usually attached to guide the completion of this section. Section 2 contains additional questions prompting further details concerning the neck, the shoulders and the lower back, for instance potential causes of injury or medical conditions in relation to those areas (20). The questionnaire is standardized to enable comparison of results between different studies. The extended version of the Nordic Musculoskeletal Questionnaire is similar in application to the original questionnaire except that it requires more details on the prevalence of musculoskeletal pain and its consequences, and that it shows initial attempt in classifying pain (21). The extended questionnaire has been tested to produce reliable data related to the onset, prevalence and consequences of musculoskeletal pain in an educated occupational cohort, hence useful as a screening tool for studies on MSDs among occupational and general populations (21).

Tailored questionnaires are also developed for the study of MSDs in relation to specific professions or tasks. Musculoskeletal Pain Intensity and Interference Questionnaire, for instance, measures and evaluates MSDs-related pain and the consequent disturbance among professional orchestra musicians (22). The Disabilities of the Arm, Shoulder and Hand (DASH) Questionnaire was jointly developed by the American Academy of Orthopaedic Surgeons, the Council of the Musculoskeletal Speciality Societies and the Institute for Work and Health to assess disability and musculoskeletal symptoms of the upper-extremity (23). The questionnaire comprises 30 items on functional activities and symptoms to which the survey subjects respond by giving a rating of 1 to 5. The items are subjective in nature, therefore, useful for both general and disease-specific studies. DASH was tested as reliable and valid in measuring functional disability among workers with MSDs of the upper-extremity in the textile industry (23). While diverse instruments were developed and refined, self-report techniques are, nonetheless, associated with inconsistent perception, comprehension or interpretation of exposure in relation to worker's literacy (24).

Observational methods involve guided assessment of worker's posture using established tools based on observation of the worker or videos taken while a task is performed (24). The most common observation methods are the use of revised NIOSH lifting equation, Rapid Upper Limb Assessment (RULA) and Rapid Entire Body Assessment (REBA) (25). The revised NIOSH lifting equation evaluates lifting task in order that incidence rate and severity of low back injuries among workers can be reduced. An outcome of the lifting equation development is the recommended weight limit (RWL). The RWL defines the weight of the load that a healthy worker can withstand over a fixed duration under specific task conditions. It is a product of six task variables, i.e. the load constant (LC), horizontal multiplier (HM), vertical multiplier (VM), distance multiplier (DM), asymmetric multiplier (AM), frequency multiplier (FM) and coupling multiplier (CM). The RWL equation, therefore, takes the form RWL = LC x HM x VM x DM x AM x FM x CM (25). Another element of the lifting equation is the lifting index (LI). The LI estimates the extent of physical stress in performing a manual lifting task. It is essentially a ratio of the load weight lifted to the RWL (25).

RULA was designed for sedentary tasks, particularly those with risk factors related to upper limb disorders and takes in account the posture adopted, forces required and muscle actions of workers (11). RULA involves the use of body posture diagrams and scoring tables through which causes of muscular fatigue can be identified. Development of RULA involved three phases i.e. development of method for recording working posture, development of scoring system and development of scale of action levels in relation to the risk level identified (11).

Rapid Entire Body Assessment (REBA) assesses working postures and movements with respect to tasks and workplace design. REBA builds upon RULA but unlike RULA, REBA can be used to evaluate both dynamic and static working postures (26). REBA takes into account working posture of the whole body and utilizes a coding system to indicate the intervention or modification of workstation required to reduce ergonomic impacts of manual handling by workers (26). Specific software can be used to aid the analysis of work sequences for different manual tasks recorded in video. Observational methods are cost-effective and uncomplicated in application but the validity of the scoring system can be questionable. Time could be a concern if videoing of work tasks is conducted (1).

Direct measurement method involves the use of devices such as Lumber Motion Monitor (LMM), Electromyography (EMG) and electrogoniometers to monitor dynamic movements and postures of workers, as well as surface electrode to measure the level of surface activation (27). LMM is a device which measures angular body segments in dynamic posture. It records the position, velocity and acceleration of the spine in three planes of motion as a function of time. LMM is carried at the back of test subjects to track their motions at work (27). EMG, on the other hand, is used to determine muscular activity in relation to workstation design. EMG studies muscular activity through analysis and measurement of electrical signals emitted during muscular contraction. Voluntary muscular contraction is associated with tension (27). Direct methods often require the use of expensive devices and software. Analysis of the measurement obtained can be complex.

While approaches of the methods of ergonomics study are often used as the basis of their classification, the classification can be further refined based on purposes, body parts and the type of work tasks. Methods used for assessing a worker's response to work load are divided into those assessing the external load or the internal load (28). The internal load indicators include heart rate, blood pressure, body temperature and muscle tension measurable with surface electromyography (EMG) (28). Occupational muscle fatigue is correlated with variations in the value of the indicators with respect to the duration of load. Nonetheless, the internal indicators are also affected by personal factors such as general health, age and gender which would complicate the establishment of correlation between a task and the risk of MSDs (14).

The external indicators include body posture, force exerted upon executing a task and the time sequence of load. Assessment of external load, hence the risk of MSDs embraces three considerations i.e. 1) entire body of the workers, 2) the load of the upper limbs, lower limbs and low back independent of the posture adopted and 3) the work tasks performed in relation to body posture, the type and value of force exerted in each phase of the task cycle and the repetitive frequency of the task (29). Methods for assessment of external load consist of general assessment and load assessment of specific areas such as low back or wrists. Roman-Liu identified and compared the most commonly used methods of external load assessment, i.e. KIM (Key Item Method), the revised NIOSH lifting equation, OWAS (Ovako Working Posture Analysis System), LUBA (Postural Loading on the Upper Body Assessment), OCRA (Occupational Repetitive Actions), SI (Stain Index), ULRA (Upper Limb Risk Assessment), REBA (Rapid Entire Body Assessment) (30). The methods are further classified based on the body area assessed and the type of work tasks as shown in the **Figure 1**. **Table 1** compares the commonly used ergonomic assessment tools.

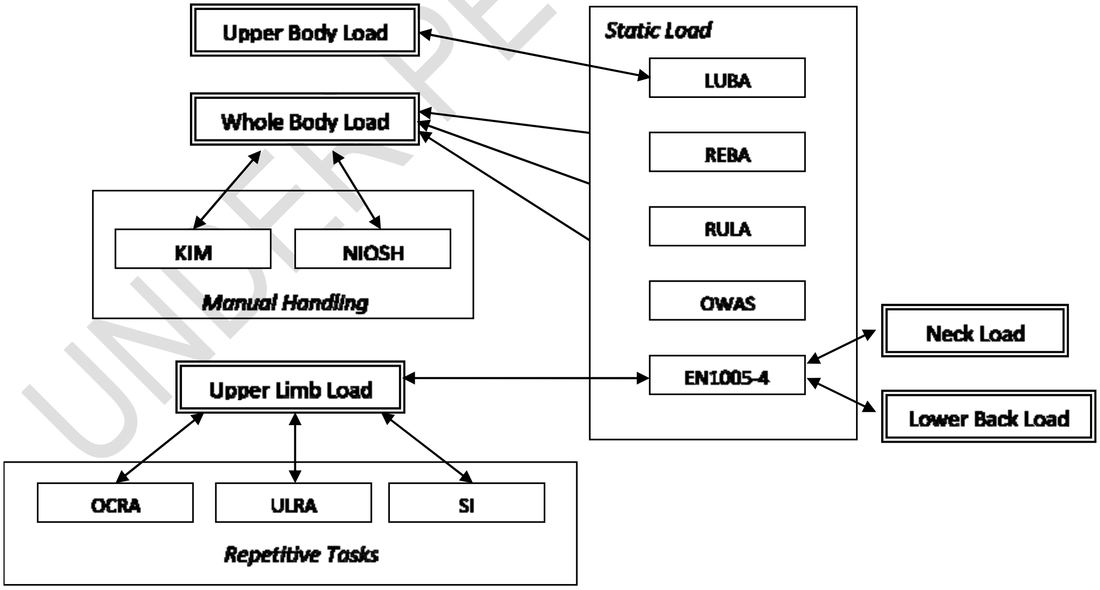

Fig. 1. Division of methods according to the body part assessed and the type of work tasks (30)

Table 1. A Comparison of the Commonly Used Ergonomic Assessment Tools (1)(11) (25)(26)(30)(31)(32)

Ergonomic Assessment Tools	Purpose	MSDs Risk Factors Considered	Body Region Considered	Type of Jobs Appropriate For	Types of Job Not Appropriate For	Limitations
NIOSH Revised Lifting Equation	Control overexertion injuries caused by manual material handling and lifting	Lifting force, posture, repetition, duration	Low back	Two hand lifting and lowering with stable loads	Repetitive tasks, static tasks, dynamic tasks, seated tasks	Exclude whole-body vibration, direct trauma to the back, or non-lifting hazards of MSDs. Cannot be used for: • 1-handed lifts • More than 8hr lifting • Seated or kneeling lifting • Tight work space lifting • Lifting unstable objects • Carrying/ pushing/ pulling tasks Cannot predict injuries to individual operators. Does not account for individual risk factors including gender, age or medical history.
LUBA	Assessment of postural loading of the upper body and limbs, either in sitting or standing posture based on experimental results of discomfort perceived.	Posture, movement, external force, vibration, contact forces	Upper body and limbs	Jobs recurring to certain extent, in a standing or sitting posture or a combination of both, involving multiple body parts.	Jobs involving the use of right and left upper limbs together.	Assess right or left upper limb individually. Does not consider force, duration and repetition, or other modifying factors. Assess postures in pre-selected work tasks.
RULA	Assess exposure to risk of MSDs of the upper limb. Quick screening of work population without assessment devices.	Repetition, awkward/ static postures, force, time worked without break	Upper arms, lower arms, wrist, trunk, neck, legs	Jobs recurring to certain extent, in a standing or sitting posture or a combination of both, involving multiple body parts.	None	Factors such as twisting, lateral bending, abduction are weighted equally regardless of the degree of movement e.g. 5° twisting or 20° twisting.
REBA	Postural analysis for musculoskeletal risk in various jobs based on body segment specific ratings within specific	Awkward postures, load/ force, coupling, activity level	Trunk, neck, legs, knees, upper and lower arms, wrists	Jobs recurring to certain extent, in a standing or sitting posture or a combination of both,	None	Factors such as twisting, lateral bending, abduction are weighted equally regardless of the degree of movement e.g. 5° twisting or 20° twisting.

	movement planes. Provide benchmark for urgency of action.			involving multiple body parts.		
ULRA (Roman-Liu et al., 2013)	Assess the upper limb load resulting from repetitive tasks, via the repetitive task indicator (RTI)	Upper limb posture, force, duration and repetitiveness.	Upper limbs	All tasks involving the upper limbs predominantly in handling materials.	Tasks where risk is associated mainly to the lower extremities.	More time required to determine upper limb posture in the arm region. Unable to assess risk related to the whole body.
OCRA	Quantifies relationship between daily number of actions actually performed by upper limbs in repetitive tasks and corresponding number of recommended actions.	Repetitiveness, force, awkward posture and movements, and lack of recovery time.	Upper limbs	Repetitive tasks involving the upper limbs predominantly in handling materials.	Tasks where risk is associated mainly to the lower extremities.	Unable to measure risk related to vibration or contact stress or disorders of the shoulder, neck or back.
Strain Index	Simple assessment of occupational risk related to MSDs of the distal upper extremities	Lifting force, push/ pull force, awkward posture, repetition, duration	Hands, wrists, forearms and elbows	Hand intensive repetitive tasks	Static tasks and awkward posture tasks	Does not consider contact stress, cold temperatures, hand-arm vibration or recovery time between exertions. Does not consider individual risk factors e.g. gender, age or medical history. Limited to MSDs risk of upper extremity. Rely on professional judgement rather than mathematical relationship between variables.

There is an increasing trend of computerizing and automating assessment of ergonomics. As early as 2002, computer software for self-assessment of ergonomic risk in the manufacturing industries was developed. The software evaluates all major system components comprising human operator, machine and equipment, workplace, environment, job and task as well as management. It is sufficiently user friendly to enable users without basic understanding of ergonomics to identify ergonomic risks in the work place, hence planning for intervention strategies to control the risks (33).

Real-time ergonomic assessment is made possible with innovation of technology. Such assessment involves placing inertial sensors at various parts of the body to create a biomechanical model. The model provides the basis for computerized RULA ergonomic assessment to enable real-time global risk assessment of MSDs. The computerized assessment generates score for each body segment monitored and provides visual feedback on risks related to MSDs to the user via a see-through head mounted display. This real-time feedback was demonstrated to significantly decrease risk of MSDs (24). The use of Kinect developed by Microsoft in 2009 as a game console has also received attention mainly because of its ability to perform facial, motion and voice recognition as well as 3D mapping. The 3D motion capture of Kinect facilitates and simplifies ergonomic assessment. However, it has few limitations such as lacking of information of body posture and smoothness of motion tracking (33).

4. CONCLUSION

This review draws attention to the prevalence of biomechanical risk factors and the consequent MSDs at workplaces which prompt thorough assessment of the risk factors. This review demonstrates a wide range of ergonomic assessment tools available for evaluation of biomechanical risk factors and recognizes that each tool has its own strengths and weaknesses. It promulgates a purpose-fit selection of ergonomic assessment tools depending on the nature of the job and the specific tasks or activities carried out by the subjects assessed. This review also recommends an integrated approach in ergonomic assessment using a combination of general and specific methods with direct measurements if permissible. It points to the possibility of real-time ergonomic assessment using inertial sensors though the cost can be prohibitive. It calls for a greater level of emphasis on ergonomics at workplaces to safeguard the health, safety and wellbeing of employees in line with the duties of employers and other relevant occupational health and safety requirements (34). There is an impetus to continuously improve the existing ergonomic assessment tools to progressively overcome their existing limitations. Real-time assessment methods can be further optimized in terms of cost, reliability and accuracy to enable their more common uses at workplaces. This review is significant to the practical aspect of ergonomic assessment through methodical presentation of the features and limitations of various postural analysis tools and recommendations for better approaches and methods in ergonomic assessment.

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