ERGONOMIC EVALUATION ON THE MANUFACTURING SHOP FLOOR: A REVIEW OF HARDWARE AND SOFTWARE TECHNOLOGIES

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ABSTRACT

The high rate of work-related musculoskeletal disorders (WMSDs) among workers on the shop floor has led to the development of various ergonomic evaluation and risk assessment tools by researchers. This paper presents a summary of existing literature reviews of hardware and software technologies developed for effective ergonomic evaluation and correct risk assessment on manufacturing shop floors. Criteria was set for the review and after comprehensive search on 14 databases, 24 studies met the criteria. Old and modern ergonomic evaluation hardware and software technologies for effective evaluation on shop floors are identified. Most literatures cited the digital human models (DHMs), which can be created on many ergonomic evaluation software tools, to be an effective ergonomic evaluation tool. Gaps are identified with the use of DHMs for ergonomic evaluations. Ultimately, this study is a contribution towards identifying adequate ergonomic evaluation and correct risk assessment tools which when implemented on the Shop floor, can lead to improved productivity, enhanced efficiency and reduced cost.

KEYWORDS: Work-Related Musculoskeletal Disorders, DHM, Risk assessment, Kinect.

1. INTRODUCTION

1.1. BACKGROUND

Ergonomics is a science that focuses its study on improved design as a remedial measure to fatigue and discomfort in humans (Openshaw and Taylor, 2006). Its objective is to optimize health, safety and productivity (HSE, 2002).

During any manual handling operation on the shop floor (Shop Floor Data Capture for Manufacturing), the safety of the operators should be ensured and such factors like ergonomics, accessibility, and reach, should be considered. When ergonomic considerations are not given top priority during the initial design of workplaces, workers are likely to get injured during manufacturing operations. However, if human factor issues are well considered in the design of the shop floors, then such factors like accessibility and reach can be predicted (Caputo et al., 2006). These can help to ensure improved efficiency of any manufacturing process, increased safety and productivity as well as reduced cost (Berlin & Kajaks, 2010; Karmakar, et. al., 2014; Mukhopadhyay, Das, & Chakraborty, 2012; Rajput, et. al., 2013; Sanjog, 2012; Sanjog, et. al., 2012).

Moreover, many manufacturing shop floors employ operators who are required to undertake manual handling activities such as lifting and carrying, which if not ergonomically executed, can result in risks that may lead to WMSDs and greatly limit workers' life and health (Savino, et. al., 2016; Valentin, et.al., 2015).

WMSDs are injuries which affect the musculoskeletal system such as muscles and tendons (Douphrate and Kolstrup, 2013; Erdinç and Yeow, 2011; Grosse et al., 2014; Halim et al., 2011; Luttmann et al., 2003; Wijk and Mathiassen, 2011). It is caused by ergonomic risk factors such as force, awkward postures, repetitive tasks, manual handling of heavy loads, prolonged standing, excessive bending, continued elbow or shoulder elevation, restrictive workstation, and improper seating (Berlin and Kajaks, 2010; Chander and Cavatorta, 2017; Erdinç and Yeow, 2011; Grosse et al., 2014; Halim et al., 2011; National Research Council, 1998; Tak et al., 2011; Ugbebor and Adaramola, 2012). It can also be caused by individual risk factors such as poor work habits (Klussmann et al., 2010; Matt Middlesworth, n.d.; OSHA-ERGONOMICS, n.d.; Soe et al., 2015; WSH (Workplace Safety and Health) Council, 2014).

About 90% of reported injuries and absenteeism are caused by WMSDs. It affects workers in many industrialised countries (BAuA, 2011; OSHA Technical Manual, n.d.). In the Great Britain, WMSDs accounted for 41% of work-related illnesses between 2015 – 2016 thereby leading to 34% of lost working days (HSE, 2016). From 2009 – 2016, manual handling was rated as the highest cause of WMSDs among the other risk factors, accounting for up to 40% of the work-related upper limb disorders and 53% of the reported work-related low back disorders. This is followed by awkward postures and repetitive tasks (HSE, 2016). Interestingly, the industries with the highest rate of occurrence of this disease are industries where lifting, carrying and other manual handling activities are still in use despite the high level of automation in the country (HSE, 2016).

Moreover, in the manufacturing sector of the United States of America, where manual handling is prevalent, WMSDs accounted for 705,800 lost days in one year as at 1995 (National Research Council, 1998), as well as 32% of the work-related illnesses reported in 2014 (NIOSH, 2016). Again, the disorder accounted for about 34% of lost days in 2017 (Bureau of Labor Statistics, 2018). Hence, operators on the shop floor involved in manual handling activities are at risk of developing the disorder.

WMSDs can be prevented by identifying, assessing and reducing the risks involved in any manual handling operation (Choy et al., 2011; Health and Safety Executive, 2016), using adequate and effective ergonomic intervention tools (NIOSH, 2016). It is therefore important to understand the risks associated with manual handling and take appropriate measures to assess and ultimately reduce the exposure to risk factors of WMSDs (Westgaard and Winkel, 2011), so that the likelihood of suffering from WMSDs such as back pain are reduced. Hence the need for effective ergonomic Intervention (Tompa et al., 2010; van Eerd et al., 2010), which when implemented on shop floors, can help to prevent work-related musculoskeletal disorders (National Research Council, 1998), optimize production, and improve workers' deliverability (Ugbebor and Adaramola, 2012; Westgaard and Winkel, 2011; Wijk and Mathiassen, 2011).

1.2. Ergonomic Risk Assessment Tools

For effective ergonomic evaluation on manufacturing shop floors, HSE recommends that a risk assessment must be carried out so as to control the risk in every workplace. This is because ergonomic Intervention and correct risk assessment using appropriate tools is a good preventive strategy for Work-Related Musculoskeletal Disorders. As a result, many companies have developed various ergonomic tools aimed at reducing the risk of developing WMSDs (Grosse et al., 2014). These tools have been employed by ergonomic evaluation experts to study and record the level of ergonomic risk factors on the shop floor. Basic risk assessment can be conducted using questionnaires, risk assessment filters, checklists and video analysis (De Magistris et al., 2013). Other tools include: the RULA (McAtamney and Nigel Corlett, 1993), Job Risk Classification Model (Mukhopadhyay et al., 2012), the Ovako Working posture Assessment System (OWAS) (Bartnicka, 2015), PATH (Posture, Activities, Tools, and Handling) (Sengupta Dasgupta et al., 2014), the Rapid Entire Body Assessment (REBA) (Chiasson et al., 2012; Löfqvist et al., 2015; Mork and Choi, 2015; Shah et al., 2016), the NIOSH Equation for lifting (Navid Arjmand et al., 2015; Potvin, 2014; Waters et al., 1998), and the Manual handling assessment chart (MAC) tool (Hernan and Paola, 2013; Pinder, 2002). Other tools include the electrogoniometry, the Burandt-Schultetus analysis for lifting tasks and the Garg's Analysis for assessing Energy Expenditure, the Lumber Motion Monitor (LMM), the 3D Static Prediction Program (3DSSPP), the American Conference of Governmental Industrial Hygienists Threshold Limit Values (ACGIH TLVs), the Snook's Psychophysical Table (Berlin and Kajaks, 2010; Bossomaier et al., 2010; Dai and Ning, 2013; Douphrate and Kolstrup, 2013; Erdinç and Yeow, 2011; Mukhopadhyay et al., 2012; NIOSH, 2007; Plantard et al., 2015; Zarzar, 2006).

RULA is an ergonomic assessment tool used for detecting the presence of ergonomic risk factors as well as indicate worker's exposure to such risks (McAtamney and Nigel Corlett, 1993), and for analysing the risks associated with Work-Related Upper Limb Disorders (Deros et al., 2015; Godilano et al., 2015). It finds wide application during the ergonomic assessment of workers' postures on manufacturing shop floors (Shah et al., 2016) and in hospitals while lifting patients (Bartnicka, 2015; Ha et al., 2014). In agriculture, studies concerning oil palm harvests showed that of the six working postures analysed, all required immediate ergonomic intervention (Deros et al., 2015). During bicycle repairing and fastening operations on the shop floor, RULA has been used to assess the risk of developing WMSDs (Daphalapurkar, 2012; Mukhopadhyay et al., 2015), etc. The advantages of the tool cannot be over-emphasised. It does not require special equipment for ergonomic risk assessment and considers biomechanical and postural load requirements of job tasks (Peppoloni et al., 2015). It is inexpensive, easy to use and hence do not require an ergonomist expert. It gives quick assessment of the postural loads on the neck, trunk, and upper limbs (Kee and Karwowski, 2007). The tool only focuses on the neck, trunk and upper limbs of humans but is very efficient when the risk assessment involves only the upper extremities of the body (Deros et al., 2015).

OWAS is an ergonomic risk assessment tool capable of estimating the postural load of an operator on a shop floor (Diego-Mas and Alcaide-Marzal, 2014). It rates work postures and classifies these postures according to the degree of their impact on the muscles of workers (Kee and Karwowski, 2007). The tool has been successfully implemented in the assessment of work postures such as seen when the tool assessed the work postures of operators as they changed brake shoes of freight wagons in a railway maintenance shop floor (Singh et al., 2015) and on bicycle maintenance shop floor (Mukhopadhyay et al., 2015). Results revealed high level of postural problems and consequently, great exposure to WMSDs among the operators and the bicycle repair workers, hence the need for immediate ergonomic intervention on the maintenance workplaces.

The REBA is a risk assessment tool which utilizes systematic approach to assess the risk of whole body exposure to WMSDs as well as risks associated with job tasks. It evaluates task-related factors such as whole body working postures, force, couplings, repetition, etc. and is inexpensive, easy to use and hence do not require an ergonomist expert. REBA has been employed for ergonomic posture assessment of numerous manufacturing shop floor operators. Recently, when workers in a garment manufacturing shop floor were assessed with this tool, the scores obtained suggested the need for immediate ergonomic intervention in the workplace (Shah et al., 2016).

The NIOSH lifting equation is a quantitative ergonomic risk assessment tool developed in 1981 by NIOSH and revised in 1991. The equation consists of the recommended weight limit, (RWL) and the lifting index, (LI) and evaluates risks involved in manual handling and lifting activities. The RWL is the maximum value of load a healthy worker can lift without developing lower back pain while LI is the weight of the lifted load (L) divided by the RWL for each task (Waters et al., 1998). It integrates biomechanical, psychophysical, and physiological criteria while utilising Load Constants (LC) with Horizontal reach (H), Vertical height (V), and lifting Frequency (F) as inputs (N Arjmand et al., 2015). M in equation 1 represents multiplier, D is distance of object, and C is the coupling/grip quality (Mark Middlesworth, n.d.). The revised NIOSH Lifting equation can identify the risk factors that leads to lower back pain during asymmetric lifting operations on the shop floor (Chung and Kee, 2000). The RWL and LI are expressed using the following task variables (Waters et al., 1998):

$$\boldsymbol{RWL = LC \times HM \times VM \times DM \times FM \times AM \times CM} \qquad 1$$

$$\boldsymbol{LI = {}^{L}/_{RWL}} \qquad 2$$

The methods for measuring the task variables are described in detail in (Mark Middlesworth, n.d.; Okimoto and Teixeira, 2009). The limitations of this tool are numerous and include lower compression force as the lifting height increases, fluctuating lifting frequency with respect to the psychophysical and physiological criteria. The equation is generally unsuitable for the risk assessment of the following; seating/kneeling to lift, lifting unstable loads, lifting in constrained workplaces, one-handed lift, and assessment of other manual handling activities. Consequently, (Potvin, 2014), has alerted ergonomists on these limitations and recommends that more specific ergonomic tools be used when designing for biomechanical, psychophysical, and physiological criteria for lifting.

The Lumber Motion Monitor (LMM), developed by the Ohio State University quantifies the risk level exposure of the spine by monitoring the lower back while working (Risk Quantification | Spine Research Institute). LMM is a quantitative tool used for 3D risk assessment of operators while working. It is usually worn on the body of the operator and this poses a great limitation as it is not convenient.

The American Conference of Governmental Industrial Hygienists (ACGIH) provides guidelines for safe lifting through the development of Threshold Limit Values (TLVs) that provide upper and lower limit guidelines for safe lifting (NIOSH, 2007; Zarzar, 2006). They adopted the ACGIH TLVs for lifting, hand-arm vibration as well as hand activity level.

The Snook’s psychophysical table is a semi-quantitative tool developed in 1978 and revised in 1991, which utilizes psychophysical methodology to provide guidance for the ergonomic risk assessment of manual handling tasks involving posture, force, frequency, etc (SNOOK, 1978; Snook and Ciriello, 1991). It can be used by even novice operators as little or no training is required before use. However, it can only be used for one task at a time.

Generally, there are two methods by which ergonomic risk factors are analysed on the shop floor – the observational technique and the instrument-based technique. The observational technique uses visual perception to evaluate the rate at which the body moves away from the neutral position. These include the OWAS, RULA, the Quick Exposure Check (QEC), and the REBA. (Diego-Mas and Alcaide-Marzal, 2014; McAtamney and Nigel Corlett, 1993; Mukhopadhyay et al., 2015; Park et al., 2015; Pinder, 2002; Sanjog et al., 2015). These tools, especially REBA, has been described as a suitable tool for risk assessment (Al Madani and Dababneh, 2016).

The instrument-based technique records risk factors using instruments (Kee and Karwowski, 2007). These tools often require offline risk assessment using such tools as the force plate, photograph, video, goniometry, inclinometers and 3D analysis using markers (Åkesson et al., 2012; Clark et al., 2012; Diego-Mas and Alcaide-Marzal, 2014; Rosário, 2014), as well as active and passive video-based systems such as the NDI and the Vicon Motion capture systems which can pose great problems for use because they are complex and bulky. Photographs and videos often produce inaccurate measurement of joint angles as a result of distortions caused by camera placement issues (Diego-Mas and Alcaide-Marzal, 2014). Some of the existing 3D systems are either very expensive, require careful setup or need to be worn on the body of the worker which causes body discomfort. An example is the wearable Inertial measurement units which measure and analyse risk factors in real-time, with real-time feedback to the workers (Sessa et al., 2015; Yan et. al., 2017).

A 3D marker-based measurement system when used by Yang and Cho (2012) to measure the relative angles of the human body during a comparison of male and female posture control pattern among computer operators, was found to yield values of the head/neck flexion angles, shoulder and elbow flexion angles as well as the wrist deviation angles and can help in data collection and analysis (Clark et al., 2012). There was successful implementation of Inclinometers based on triaxial accelerometers to measure the flexion, extension and lateral extension angles of the human joints by Åkesson et. al. (2012). A photogrammetric analysis method was used by (Naddeo et al., 2015) to measure joint angles of the Neck, shoulders, elbow and wrists for comfort evaluation of upper extremities of the human body. Microsoft Kinect has been recommended as an alternative method for risk assessment because of its low cost and 3D motion capture capabilities (Diego-Mas and Alcaide-Marzal, 2014; Dutta, 2012; Ho et al., 2016; Mgbemena et al., 2018, 2017, 2016; Rosário, 2014).

This review paper aims at studying previous review papers that have conducted systematic and comprehensive studies on ergonomic evaluation on shop floors between 2010 to 2015, to identify the hardware and software utilised for ergonomic evaluation on the shop floor.

2. METHODS

2.1. Search Strategy

A systematic search was conducted to identify reviews done on ergonomic evaluations on the shop floor.

The searches were conducted on 14 databases which included EBSCO, Emerald, Research gate, Cochrane Library, ProQuest (ABI/INFORM), Annual Reviews, Scopus, ABI/INFORM Global, Google, Google Scholar, IEEEXplore, SAE, SPIE DIGITAL LIBRARY, INDERSCIENCE and ScienceDirect.

The review was limited to review papers written only in English Language and the search words include: “Ergonomics”, AND/OR “Evaluation”, AND/OR “Shop floor”. Combination of words like “Ergonomic

Evaluations on Shop floor" was also used. The search was restricted to review papers published within 2010-2015.

2.2. Search Results

Related papers were first screened by title and abstract and a total of 122 articles were initially selected for screening. Duplicates were removed, and the full texts of these papers were thoroughly studied resulting in the final selection of 24 review papers with 1589 citations, which met the inclusion criteria as stated in 2.1.

2.3. Paper Analysis

A comprehensive analysis of all the review papers studied in this review of reviews are shown in tables 1-5.

Table 1. Analysis of 2010 Reviews

S/N	AUTHORS & COUNTRY	JOURNAL	PURPOSE OF THE REVIEW	NUMBER OF PAPERS REVIEWED	DURATION
1	Berlin and Kajaks (2010). Sweden Canada	International Journal of Human Factors Modelling	To compile and examine time-related ergonomic terms for the benefit of introducing such concepts into DHMs.	75	1990-2009
2	Blanchonette (2010). Australia	Technical Report by Air Operations Division. DSTO Defense Science and Technology Organisation	To review the JACK tool (version 5.1) with reference to its features to ascertain its relevance to the assessment of seated workstations.	35	1957-2004
3	Bossomaier et al, (2010). Australia Italy	Proceedings on the 24th European Conference on Modelling and Simulation, ECMS 2010	To review the main scientific approaches used to design workstations ergonomically during the past two decades.	65	1976-2009
4	Tompa, et. al., (2010). Canada. USA.	Journal of Occupational Rehabilitation	To review the cost-effectiveness of ergonomic interventions to ascertain if investing on it is worthwhile.	30	1992-2009

Table 2. Analysis of 2011 Reviews

S/N	AUTHORS & COUNTRY	JOURNAL	PURPOSE OF THE REVIEW	NUMBER OF PAPERS REVIEWED	DURATION
1	Erdinc and Yeow (2011) Turkey Malaysia	International Journal of Production Research	To review five field experiment ergonomics studies so as to strengthen the external validity between ergonomics and quality.	43	1991-2009
2	Halim and Omar, (2011) Pakistan	International Journal of Research and Reviews in Applied Sciences	To disseminate information on health effects, assessment methods, and control measures associated with prolonged standing jobs in industrial workplaces.	60	1972-2010
3	Westgaard and Winkel (2011) Norway, Denmark, Sweden	Applied Ergonomics	To identify occupational musculoskeletal and mental health effects of production system rationalization as well as organizational-level measures that may improve health outcome with respect to ergonomic interventions.	359	1959-2010
4	Wijk and Mathiassen (2011) Sweden	Scandinavian Journal of Work, Environment & Health	To review theories on change processes upon which ergonomic interventions – both implicitly or explicitly – have been based	100	1983-2010

Table 3 Analysis of 2012 Reviews

S/N	AUTHORS & COUNTRY	JOURNAL	PURPOSE OF THE REVIEW	NUMBER OF PAPERS REVIEWED	DURATION
1	Mukhopadhyay et al, (2012) India	International Journal of Advanced Computer Research	To evaluate how research in DHM has finally brought about an enhanced HCI in the context of Computer-Aided ergonomics or Human-Centric Design.	78	1979-2010
2	Sanjog et al, (2012a) India	International Journal of Computer Application	To review extensively, the relevance of DHMs as a tool for effective ergonomic evaluation of existing or proposed manufacturing workstation and to encourage industries in developing countries to adapt the technology	53	1980-2012
3	Sanjog et al, (2012b) India	Proceedings of the International Summit on Human Simulation 2012	To highlight major industry specific applications of Digital Human Modeling (DHM) software	59	1996-2012
4	Sanjog et al, (2012c) India	Proceeding of International Conference on Recent Trends in Computer	To review the status of using DHM software in production shop floors and to highlight its advantages and shortcomings with the aim of making	33	1996-2012

		Science and Engineering	industries and researchers to develop more advanced applications		
5	Thorvald et al, (2012) United Kingdom, Sweden	International Journal of Human Factors Modelling & Simulation	To review previous approaches to ergonomic evaluation, fill a gap in the digital human modelling that will help a user with little or no knowledge of cognitive science to design and evaluate a human-product interaction scenario.	50	1948-2012
6	Ugbebor and Adaramola (2012) Nigeria	Work: A Journal of Prevention, Assessment and Rehabilitation	To review the causes of work related musculoskeletal disorders (WMSD's) and other ergonomic related workplace incidence rate so as to develop a model that can analyse and solve the ergonomic problems in the workplace	13	1991-2004

Table 4. Analysis of 2013 Reviews

S/N	AUTHORS & COUNTRY	JOURNAL	PURPOSE OF THE REVIEW	NUMBER OF PAPERS REVIEWED	DURATION
1	Dai and Ning (2013) USA	ISARC 2013 - 30th International Symposium on Automation and Robotics in Construction and Mining, Held in Conjunction with the 23rd World Mining Congress	To review state of practice and research in the assessment of risks of MSDs among construction workers, in which several biomechanical models have been developed to evaluate joint and tissue loading with the aid of state-of-the-art remote sensing technologies	58	1970-2013
2	Douphrate et al, (2013) USA	Journal of Agromedicine	To review the use of ergonomic tools such as electrogoniometry to measure exposures to risk factors for WMSD among dairy farm workers and propose ergonomic interventions to reduce this risk.	61	1977-2013
3	Patel et al, (2013) India	Advanced Engineering Forum	To provide an up-to-date research in virtual ergonomics evaluation technology through the use of DHM and its applications in agriculture	43	1997-2012
4	Rajput et al, (2013) India	International Journal of Science and Research	To discuss the current research on digital human modelling, their capabilities and issues generating with the growing demands of technology	18	1966-2009

Table 4. Analysis of 2014 Reviews

S/N	AUTHORS & COUNTRY	JOURNAL	PURPOSE OF THE REVIEW	NUMBER OF PAPERS REVIEWED	DURATION

1	Karmaka et al, (2014) India	International Journal of Engineering Research and Applications.	To identify the status of DHM application and research in India and propose solutions to encourage its wide adoption.	58	1995-2013
2	Prabhu et al, (2014) United Kingdom, Singapore	Proceeding of 8th International Conference on Digital Enterprise Technology, DET 2014 – Disruptive Innovation in Manufacturing Engineering towards the 4th Industrial Revolution	To study the method for dynamic alignment control using infrared light depth imagery to enable automated wheel loading operation for the trim and final automotive assembly line.	9	2005-2012
3	Reinvee and Jansen (2014) Estonia	Agronomy Research	To investigate the main aspects of tactile sensors and its effectiveness in data collection on the shop floor for ergonomic evaluation.	43	1989-2011
5	Singh et al (2014) India	Indian Journals	To investigate and review the use of computerized human manikins for development and fabrication of ergonomic products	45	1966-2013

Table 5. Analysis of 2015 Reviews

S/N	AUTHORS & COUNTRY	JOURNAL	PURPOSE OF THE REVIEW	NUMBER OF PAPERS REVIEWED	DURATION
1	Grosse et al, (2015) Germany Canada	International Journal of Production Research	To propose a conceptual framework for integrating human factors into planning models of order picking activities.	162	1993-2014
2	Plantard et al, (2015) France, Canada	Sensors	To study the developmental trends in the methods of data collection in workplaces so as to analyze human postures and movement for better evaluation of the risk factors in the workplace	39	1991-2015

This paper seeks to identify from literature, the ergonomic tools for effective evaluation and correct risk assessment on manufacturing shop floors.

3. Results

3.1. The Digital Human Modelling Technology

The Digital Human model (DHM), which is a very effective tool for ergonomic evaluation on the shop floor, has been employed on manufacturing shop floors as a tool for improving existing/ proposed manufacturing shop floors (Sanjog et al., 2012a, 2012b), workstation layout, workflow simulation, assembly accessibility, reach as well as for analysis of clearance, strength capability and safety (Rajput et al., 2013; Sanjog et al., 2012a, 2012b). DHM also finds wide application in design for assembly feasibility, process compatibility, posture and movement simulations, vision simulation, joint dependent comfort/discomfort evaluations, maximum force calculations, center of gravity analysis, biomechanical analysis and unintentional/ hazardous human machine contact/interaction (Sanjog et al., 2012a, 2012b).

The application of DHM is useful for reduction of project time-scale (Karmakar and Patel, 2014), decreased design and manufacturing cost (Berlin and Kajaks, 2010; Karmakar and Patel, 2014; Mukhopadhyay et al., 2012), lower occupational hazards (Karmakar and Patel, 2014), improved quality of products (Karmakar and Patel, 2014; Mukhopadhyay et al., 2012), increased productivity and greater efficiency (Karmakar and Patel, 2014; Mukhopadhyay et al., 2012). The DHM functions by enhancing the visualization of the interaction of a human-workstation system both in the vehicle manufacturing shop floor (Crizzle, 2013), in which it is employed to evaluate the optimal relation between safety and comfort, as well as in an agricultural shop floor (Patel et al., 2013).

The history of the development of the DHM dates to the early 1960's with the emergence of the Computer Aided Design (CAD). The CAD development made the aerospace and automobile manufacturers see the need to convert their design processes into a virtual environment (Blanchonette, 2010)**. Boeman Mannequin** (Blanchonette, 2010; Singh et al., 2014) is the first human ergonomic modelling tool ever developed, followed by the computerized biomechanical man model called the **Combiman** (Blanchonette, 2010; Bossomaier et al., 2010; Singh et al., 2014). Next is the cybernetic man model known as the **Cyberman** (Blanchonette, 2010; Singh et al., 2014).

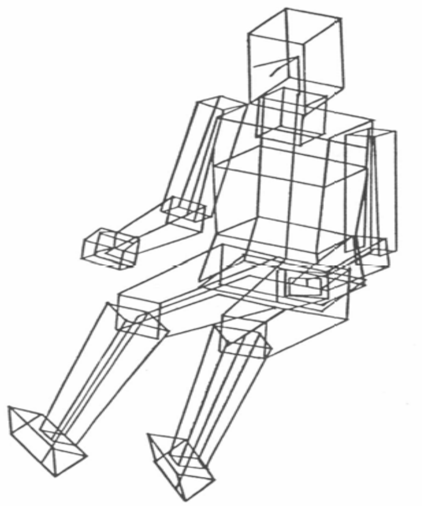

Fig.1 The Boeman Mannequin (Blanchonette, 2010)

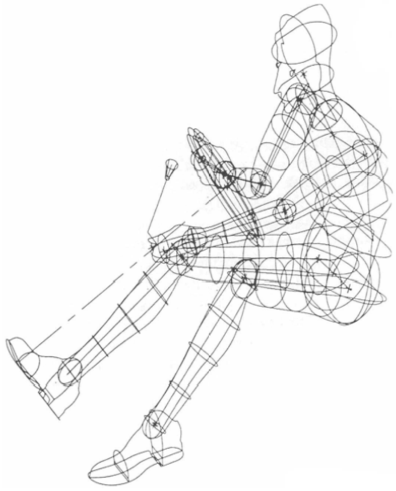

Fig.2 The Cybernetic Man-Model (Blanchonette, 2010)

The various ergonomic evaluation tools on which modern digital human models can be created include **MannequinPro** (Blanchonette, 2010; Singh et al., 2014), **Jack** (also known as Tempus) (Berlin and Kajaks, 2010; Blanchonette, 2010; Bossomaier et al., 2010; Mukhopadhyay et al., 2012; Singh et al., 2014; Thorvald et al., 2012), **Ramsis** (Blanchonette, 2010; Bossomaier et al., 2010; Mukhopadhyay et al., 2012; Singh et al., 2014; Thorvald et al., 2012), **Safework** (Berlin and Kajaks, 2010; Blanchonette, 2010; Mukhopadhyay et al., 2012; Singh et al., 2014), **Sammie** (Blanchonette, 2010; Singh et al., 2014; Thorvald et al., 2012), and **Delmia** (Berlin and Kajaks, 2010; Singh et al., 2014). The computer manikins (DHM) which are algorithms specifically developed for ergonomic evaluations include **Anybody Technology** (Berlin and Kajaks, 2010; Bossomaier et al., 2010; Mukhopadhyay et al., 2012), **3DSSPP$^{\text{TM}}$** (Mukhopadhyay et al., 2012)**, Tecnomatic** (Singh et al., 2014), **SantosHuman** (Crizzle, 2013; Singh et al., 2014)**, HumoSim** (Crizzle, 2013), **HandiMan** (Crizzle, 2013)**, Hadrian** (Singh et al., 2014)**, Santos** (Berlin and Kajaks, 2010; Singh et al., 2014) and **Ergonaut** (Patel et al., 2013)**,** which is used in virtual Environment for ergonomic evaluations.

Other computer-aided methodologies for ergonomic evaluations on shop floors include the **Virtual Environment** (Bossomaier et al., 2010; Singh et al., 2014), **ErgoSHAPE** (Bossomaier et al., 2010), **Human** (Bossomaier et al., 2010), **Ergoman** (Bossomaier et al., 2010), and **ANNIEErgoman** (Bossomaier et al., 2010).

Fig. 3 Application of DHMs in various Industries (Karmakar and Patel, 2014).

One of the gaps identified from the use of DHM as an ergonomic evaluation tool is the incorporation of cognitive ergonomics into DHM. Thorvald et al., (2012) tried to solve this problem by developing a mathematical model that incorporates the two, but the model was not tested. Another gap is found in the application of DHM to solve time-related ergonomic factors in relation to physical workload (Berlin and Kajaks, 2010).

3.2. Software Technologies

The analysis of the software technologies studied in this review is two-fold:

i. The Ergonomic evaluation tools
ii. The Human Ergonomic Modelling Tools (Computer Manikins)

Table 6 Ergonomic Evaluation tools

S/N	NAME OF SOFTWARE	DESCRIPTION	PAPERS WHERE SOFTWARE IS EMPLOYED
1	Safework	Initially developed at the Ecole Polytechnique, Canada, in the 1980s and is now developed by Dassault Systemes Offer basic postural ergonomic tools such as the NIOSH equation, RULA and Garg's Metabolic equation.	• Berlin and Kajaks, 2010 • Blanchonette, 2010 • Mukhopadhyay et al, 2012 • Singh et al, 2014 • Bossomaier et al, 2010
2	Delmia Human	Offer basic postural ergonomic tools such as the NIOSH equation, RULA and Garg's Metabolic equation. It is widely used in industrial manufacturing and product design in multiple industries including: automotive, aerospace, defense, heavy machinery, etc. In the automotive industry, it is used in the complete life-cycle of the vehicle from Concept to Product Design, Product Assembly and Product Servicing.	• Berlin and Kajaks, 2010 • Singh et al, 2014
3	JACK	Developed at the University of Pennsylvania in the mid-1980s to support the design and development of workspaces, with the emphasis on optimizing the human machine interface. It contains a high-level functioning manikin skeleton that allows for many degrees of freedom and calculation of internal joint torques. It also contains the University of Michigan's 3D static strength prediction program module and can stream real-time motion data.	• Berlin and Kajaks, 2010 • Blanchonette, 2010 • Mukhopadhyay et al, 2012 • Singh et al, 2014 • Bossomaier et al, 2010 • Thorvald et al, 2012
4	MannequinPro	This can create male and female models based on 11 anthropometric data. Mannequins can be created based on a range of percentile statures from 2.5 to 97.5 percent. In addition, the mannequin's joints have a realistic range of motion.	• Blanchonette, 2010 • Singh et al, 2014
5	SAMMIE	This means System for Aiding Man-Machine Interactive Evaluation (SAMMIE) was originally developed at the University of Nottingham and subsequently at Loughborough University. It is a 3-dimensional system which consists of man-model with comfortable maximal joint	• Blanchonette, 2010 • Singh et al, 2014 • Thorvald et al, 2012

		angle constraints and a powerful workplace modelling system.	
7	RAMSIS	Can be employed in the Computer-Aided Design (CAD) system to develop seat constructions in vehicle mock-up	• Crizzle et al, 2014 • Mukhopadhyay et al, 2012 • Singh et al, 2014 • Thorvald et al, 2012 • Bossomaier et al, 2010

Table 7 Human Ergonomic Modelling Tools (Computer Manikins)

S/N	NAME OF SOFTWARE	DESCRIPTION	PAPERS WHERE SOFTWARE IS EMPLOYED
1	Anybody Technology	This is a DHM tool that can calculate the Biomechanical attributes and predict physical fatigue and potential disorder risk. It has the capability to drive dynamic models as well as estimate muscle recruitment patterns using inverse dynamics optimization techniques	• Berlin and Kajaks, 2010 • Mukhopadhyay et al, 2012 • Bossomaier et al, 2010
2	Santos	Contains optimization-based motion prediction capability.	• Berlin and Kajaks, 2010 • Singh et al, 2014
3	Boeman	This was developed by the Boeing company in the late 1960s to assess pilot accommodation in aircraft cockpits It consists of 23 joints and its size was based on anthropometric data for a 50th percentile man. The segment lengths could be scaled to any dimension, although the depth and breadth of the segments could not be changed. The program was written in FORTRAN IV and ran on a CDC 6600 computer. The input describing the mannequin and environment was entered in batch mode and the output was displayed on a plotter as graphics capable terminals were not common in the late 1960s.	• Blanchonette, 2010 • Singh et al, 2014
4	Combiman	A computerized Biomechanical man-model developed at the university of Dayton. The Mannequin can be created based on anthropometric data and can produce field of view plots as well as determine reach. It can also predict strength based on empirical data.	• Blanchonette, 2010 • Bossomaier et al, 2010 • Singh et al, 2014

5	Cyberman	This is a Cybernetic man-model developed in the 1970s by the Chrysler Corporation for the in-house design and evaluation of automobiles. The mannequin consists of 15 segments of any required size but no joint constraints	• Blanchonette, 2010 • Singh et al, 2014
6	SantosHuman	A Digital Human Model developed at the University of Iowa. It is a high-fidelity model using biomechanics, physics optimization, and clinical evaluation to simulate human activities with ergonomic analysis, human performance, human performance analysis, and human systems integration with predictive posture analysis	• Crizzle et al, 2014 • Singh et al, 2014
7	HumoSim	A DHM developed at the University of Michigan.	• Crizzle et al, 2014
8	HandiMan	A DHM developed at the University of Lyon, France. It can digitize the egress motion of older adults with the aim of creating more realistic DHMs.	• Crizzle et al, 2014
9	ANNIE-Ergoman	Digital Human Model developed to work with CAD systems and which utilizes application of Neural Networks in integrated ergonomics.	• Bossomaier et al, 2010
10	ErgoShape	This is a design-oriented ergonomic tool for AUTOCAD and useful for effective workstation ergonomic evaluation.	• Bossomaier et al, 2010
11	Human	Digital Human Model developed to work with CAD systems for effective workstation ergonomic evaluation.	• Bossomaier et al, 2010
12	Ergoman	Digital Human Model based on the ELUCID CAD system software and useful in the choice of morphotypes, evaluations of joint angle limits, field of vision, collision detection, etc.	• Bossomaier et al, 2010
13	Ergonaut	A DHM tool used in the Virtual Environment to analyse reach envelope, visual field and force as well as virtual and real data in a mixed mock-up	• Patel et al, 2013
14	Tecnomatix	This is based on the first DHM program designed and used for NASA in the early 1980's. It is a human simulation and modelling software for ergonomic analysis of human-performed tasks on manufacturing shop floors.	• Singh et al, 2014
15	HADRIAN	Human Anthropometric Data Requirements Investigation and Analysis is a 3D human modeling and task analysis tool that works together with SAMMIE to develop products that people with disabilities as well as the elderly can use.	• Singh et al, 2014

16	3DSSPP™	The 3D Static Prediction Program (3DSSPP) developed at the University of Michigan is used to obtain the posture data of operators, analyse and display the outputs in compliance with the NIOSH guidelines (Center for Ergonomics, 2016). The tool, which is DHM-based, can predict such factors as push, pull, lifts, etc. and provide information about the posture, force and anthropometry data of the operator. It can perform the function of posture analysis and posture prediction and have the capability to visualise virtual humans in 3D (Ma et al., 2011). It can also evaluate trunk twists and bends as well as workplace design and re-design. (Ma et al, 2011).	• Mukhopadhyay et al, 2012

3.5 Developmental Trends in Methods of Data Collection for effective Ergonomic Evaluation on the Shop floor

The developmental trends in the methods of data collection on shop floor span from self-report, such as Interviews (Erdinç and Yeow, 2011; Plantard et al., 2015; Ugbebor and Adaramola, 2012), Checklists (Plantard et al., 2015; Ugbebor and Adaramola, 2012), and Questionnaires (Plantard et al., 2015), to observational methods which is commonly used in industries. This involves the use of video-based capture systems to collect data which is analyzed using ergonomic tools (Bossomaier et al., 2010; Erdinç and Yeow, 2011; Plantard et al., 2015; Ugbebor and Adaramola, 2012). The work methods which are captured by means of video tapes are later analysed by extracting the video-based posture assessment method capable of measuring trunk angles. However, this method has been found to be inaccurate. The trend moved from video to direct methods of data collection using sensors attached to an operator's body (Dai and Ning, 2013; Plantard et al., 2015). Such sensors include goniometers, inclinometers, as well as optical sensors (Dai and Ning, 2013) and are used to analyse human body mechanics with markers attached directly to specific anatomic points on the operator's body so as to record the motion data. Other sensors employed in this category include the inertial sensors such as the accelerometers and the gyroscope sensors which can assess human pose but is disturbed by the environmental conditions such as vibration (Plantard et al., 2015). However, many operators found it uncomfortable to wear markers while working. The use of tactile sensors for data collection on the shop floor for ergonomic evaluations was introduced and such factors as the sensor dimensions, sensel density, robustness and accuracy were put into consideration while choosing the tactile sensors (Reinvee and Jansen, 2014).

Moreover, to overcome the limitations posed by using marker-based sensors, low-cost depth cameras such as the Microsoft Kinect Sensor was introduced, which provides an easy-to-use, marker less, calibration-free and cheap alternative. This 3D sensing technique with marker-less sensor-based biomechanics can capture and analyze complex and dynamic human motions in real workplaces (Mgbemena et al., 2017).

Researchers describe it as an imaging sensor capable of capturing depth of each image pixel and can also detect and track the human body segments and joints, operator's postures as well as classify the motion as either ergonomic or non-ergonomic (Dai and Ning, 2013; Plantard et al., 2015).

Based on the developmental trends of data collection on the shop floor studied in this review, we can recommend the use of the low-cost infrared light depth imaging systems which are popular in the gaming industry like Microsoft Kinect™ or Asus Xtion. These possess the ability to generate real-time spatial data in all 3 axes at the same time. The proposed hardwares are 3D motion capture system suitable for recording human motion and posture in the x, y, and z directions for shop floor ergonomic assessment (Prabhu et al., 2014).

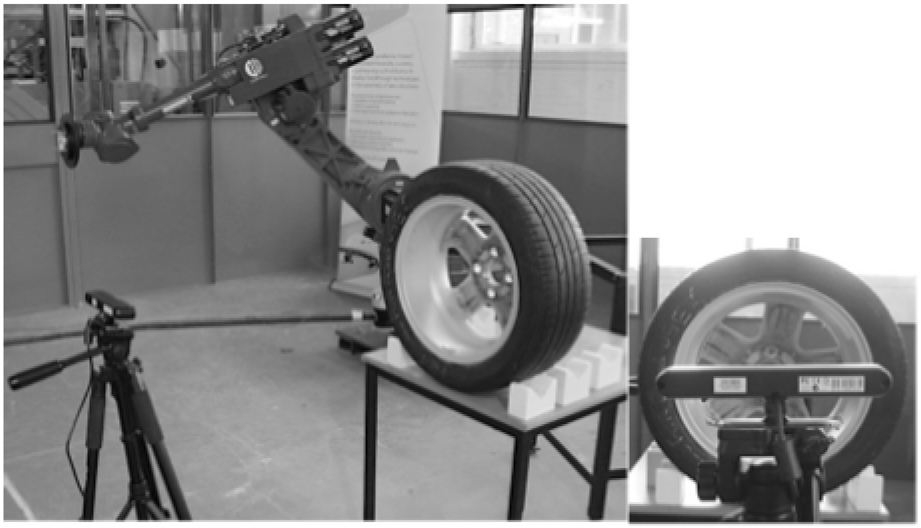

Fig. 4 Data capture of Wheel parameters using Xtion (Prabhu et al., 2014).

A summary of the hardware technologies is presented on table 3.

3.6 Hardware Technologies

A comprehensive analysis of the hardware technologies studied in the review are shown in the table 8.

Table 8 Hardware Technologies

S/N	NAME OF HARDWARE	DESCRIPTION	PAPERS WHERE HARDWARE IS USED.
1	Video Tape System	Consists of a desktop computer equipped with digital video, video tape recorder, a desktop Computer and a playback Technology. It produces a video-based posture that measures trunk angles and angular velocities in industrial Workplaces.	• Bossomaier et al, 2010 • Ugbebor and Adaramola, 2012 • Plantard et al, 2015 • Erdinc and Yeow, 2011

2	Goniometer Sensors	These are sensors designed for the measurement of Limb angular movement. They are attached across joints and connected to the Biometric instruments which records data on human activity and provide high accuracy for epidemiologic studies.	• Dai and Ning, 2013 • Plantard et al, 2015
3	Inclinometer Sensors	These are high precision sensors which measures horizontal and vertical angular inclination at high resolutions.	• Dai and Ning, 2013
4	Optical sensors	These are sensors used for a variety of Industrial applications ranging from motion detection to light detection.	• Dai and Ning, 2013
5	Accelerometer Sensors	These are electromechanical devices used to measure changes in velocity over time. They are employed in fall detection, shock detection and sensing orientation as well as vibration.	• Plantard et al, 2015
6	Gyroscope sensors	These sensors, based on the MEMs technology, senses and measures the angular rate of an object under complex and severe operating conditions.	• Plantard et al, 2015
7	Tactile Sensors	This device measures information arising from physical interaction with its environment. Tactile sensors are generally modelled after the biological sense of cutaneous touch which is capable of detecting stimuli resulting from mechanical stimulation, temperature, and pain	• Reinveel and Jansen, 2014
8	Microsoft Kinect Sensors	This device, which is based on Prime Sense technology (Tel Aviv, Israel), comprises of an infrared projector of structured light and an infrared camera that returns a depth image of the scene at 30 Hz	• Plantard et al, 2015 • Prabhu et al, 2014 • Dai and Ning, 2013
9	Asus Xtion	This device, which is also based on Prime Sense technology, is very much like the Kinect and performs similar function. The only difference being that Kinect hardware requires an external power supply, whereas the Xtion can be powered via the USB port.	• Prabhu et al., 2014

4. Discussion

WMSDs has been found to be caused by many factors such as prolonged standing or sitting in workplaces, repetitive motion, awkward postures, excessive bending, and continued elbow or shoulder elevation. This calls for implementation of ergonomic intervention practices on the shop floor. As a result, development of ergonomic evaluation tools for measuring the rate of exposures to risk factors for WMSD has been the focus of most research in recent years. These tools include the electrogoniometry, the RULA, the Job Risk Classification Model, the OWAS, the REBA, PATH, the NIOSH Equation for lifting, the Burandt-Schultetus analysis for lifting tasks and the Garg's Analysis for assessing Energy Expenditure.

Since the 1960's, various computer-aided tools have emerged for evaluating ergonomics on manufacturing shop floors which include Boeman, Combiman, Cyberman, Ergoman, Jack, Safework, RAMSIS, SAMMIE. These are all human models and the software used to generate these models (DHMs) are called computer manikins and include Tecnomatic, Delmia, SantosHuman, Jack, 3DSSPP.

For effective ergonomic evaluation on shop floors, there is need for accurate data collection using adequate tools. Self-report such as interviews and questionnaires were used to collect data for ergonomic evaluations, but this method was complemented by the observation method such as video tapes which were used to capture data with the extraction of critical postures during analysis (Bossomaier et al., 2010; Erdinç and Yeow, 2011; Ugbebor and Adaramola, 2012). Photographs and videos have limitations such as inaccurate measurement of joint angles because of distortions caused by camera placement issues. Wearable marker-based sensors were later introduced and identified as good hardware for data collection on shop floor. Tactile sensors were used with the recommendation that the dimensions, density, robustness, and accuracy of the sensors be considered while choosing for sensor as a motion capture tool (Reinvee and Jansen, 2014).

In a bid to get simpler, less complex tools for ergonomic analysis, researchers have been developing and implementing ergonomic risk assessment tools which can be used for either initial or detailed risk assessment and evaluation. The 3DSSPP, which is a DHM-based system, requires manual inputs of needed parameters by experts. Its developers have proposed that it should not be used alone when predicting static strength and job design requirements. Again, the tool is difficult to use by novice operators as it requires sufficient training before use. The Snook's psychophysical table is most suitable for preliminary assessment though it can only be used for only one task at a time. The NIOSH lifting equation is not versatile and therefore cannot assess varieties of tasks. The LMM is usually worn on the body of the operator and therefore causes body discomfort. One major limitation of the ACGIH is that they do not assess risks posed by all manual handling operations.

Between 2010 and 2015, many ergonomic assessment tools were identified from this study. The review identified DHM-based systems such as JACK, as an effective ergonomic assessment tool. Its major application and relevance in assessing various workstations, which include seated workstations, were studied with the view that it can be applied to variety of workstations. The cost implication of using DHM-based systems were also studied and the study showed that investing on DHM systems for ergonomic assessment is worthwhile. Industries in developing countries are therefore encouraged to adapt DHM technology for effective ergonomic assessment.

While some researchers have identified the DHM as an effective ergonomic evaluation tool useful for visualising and assessing risk factors such as postures without using real humans, some other researchers have found limitations in its use for ergonomic evaluations of shop floors. These limitations include the inability of the model to consider task duration and repetition which are risk factors that can lead to WMSDs(Berlin and Kajaks, 2010)(Berlin and Kajaks, 2010)(Berlin and Kajaks, 2010)(Berlin and Kajaks, 2010). Again, DHMs fail to incorporate cognitive ergonomics in its assessment. Moreover, for ergonomic assessment using the DHM, human anthropometric data are often pre-recorded, scanned or manually imposed on the DHM, which often lead to errors, inaccuracies and waste time. They are most suitable for ergonomic assessment during product and workplace design. We recommend that future work should consider these factors while using DHMs for ergonomic evaluations.

5. Conclusions

This summary of reviews is the result of a systematic and comprehensive search on several databases on the ergonomic evaluation on manufacturing shop floors.

Timely ergonomic interventions do not only lead to workers' satisfaction but also leads to improved productivity and reduced cost. It is the best preventive strategy to WMSDs as it helps to identify as well as reduce the worker's exposure to risk factors for developing WMSDs. High task repetition, awkward postures, forceful exertion, vibration and manual handling of heavy loads, if not identified and assessed, can lead to WMSDs in the workplace. For effective ergonomic interventions on shop floors, appropriate assessment tools are required to not only reduce the risk of WMSDs but to also improve productivity, improve quality, reduce rejection costs as well as increase revenue. Selecting the correct tool requires basic knowledge of the major issues that can lead to risks and injury.

The study reveals that for the five-year focus, the developmental trend in the methods of data collection on shop floor for ergonomic evaluation moved from direct observations using checklists, interviews and video tape recordings and analysis; to direct methods of data collection using sensors attached to the operator's body. Later, markers attached directly to specific anatomic points on the operator's body, tactile sensors, 3D sensing technique with marker-less sensor-based biomechanics such as the Microsoft Kinect, were introduced. Based on these trends, we recommend the use of the infrared light depth imaging systems like Microsoft Kinect™ or Asus Xtion™ as hardware for data collection for effective ergonomic evaluation and correct risk assessment on the shop floor. This is because the recommended hardware is easy to use, requires less time for data processing and does not interfere with the work process – all at low cost (Mgbemena et al., 2017; Prabhu et al., 2014). They are also capable of generating accurate Kinematic information required to fill an ergonomic assessment grid with an opportunity for real-time feedback.

Ergonomic risk assessment tools such as Job Risk Classification Model, OWAS, REBA, and RULA, were identified in the study as tools used to ascertain/assess the level of ergonomic risk in any shop floor. Their limitations were also identified.

Finally, the DHM technology was found to be the most effective ergonomic evaluation tool which when used on shop floors, can help to visualize the effective interaction of a human-workstation system. They can be created on ergonomic evaluation software such as the Ergoman, Jack, Safework, RAMSIS, SAMMIE, and 3DSSPP. which enables real-time simulation and evaluation of workplaces.

Future work should consider developing valid mathematical models that incorporates cognitive ergonomics in DHMs. DHMs should also be developed to assess such factors as the task duration and repetition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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