Ergonomic risk assessment in DHM tools employing motion data – exposure calculation and comparison to epidemiological reference data

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Abstract: Digital human modelling (DHM) allows ergonomic risk assessment to be performed at early stages of design and development. Such assessment is typically based on observational methods, which do not take advantage of the potential of DHM tools to provide precise posture and motion data. This paper describes and illustrates an alternative assessment approach employing DHM tools, inspired by risk assessment based on direct measurements. A literature survey established a reference database of epidemiological associations between exposure and wrist-related disorders. This approach is illustrated by a DHM simulation of a car assembly task. Wrist posture and motion were simulated and compared to the database, predicting the prevalence of work-related musculoskeletal disorders on the basis of direct measurements.

Keywords: biomechanical load; digital human modelling; wrist; repetitive strain injuries; direct measurements; exposure-response relationship; physical workload; work-related musculoskeletal disorders; risk assessment.

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1 Introduction

Work-related musculoskeletal disorders (WMSDs) are often associated with a reduction in the quality of the worker's life and entail considerable costs to businesses and society, both directly and through loss of production (European Agency for Safety and Health at Work, 2010). In European countries in 2005, such disorders comprised almost 40% of all occupational diseases (European Agency for Safety and Health at Work, 2010), and only a slightly lower proportion (32%) in the USA (Bureau of Labor Statistics, 2014). The costs of WMSDs involving the upper limb due to, e.g., production losses, costs for replacing the worker, as well as the costs of rehabilitation and disability pensions have been estimated to be 0.5–2% of the gross national product (Pinder et al., 2007).

Musculoskeletal disorders include injuries to and disorders of the muscles, nerves, joints, tendons and ligaments most commonly involve the wrist, shoulder and back, although any part of the body may be affected. Ergonomic epidemiology has revealed that several major occupational factors related to various aspects of physical load during work [e.g., awkward postures, high force and repetitive movements (Kuorinka et al., 1995; David, 2005; Bernard, 1997; Putz-Anderson, 1988; Buckle and Devereux, 2002; Sluiter et al., 2001; Levy, 2006)] interact in connection with the development and aggravation of musculoskeletal injuries (Winkel and Mathiassen, 1994; Devereux et al., 2002; Armstrong et al., 1993; Roquelaure et al., 2006). Exposure to such factors is often quantified in terms of *intensity* (-how much), *frequency* (-how often) and *duration* (-how long) (Kuorinka et al., 1995), and the accumulated exposure i.e., the load dose, employed for assessing dose-response relationships and the risk for musculoskeletal disorders. WMSDs of the upper limb are typically associated with repetitive mechanical exposure causing disorders referred to as 'umulative trauma disorders' (CTDs) (Armstrong, 1986; Silverstein et al., 1986), 'repetitive strain injuries' or 'overuse syndromes' (Giersiepen and Spallek, 2011; Browne et al., 1984) which are umbrella terms for occupational origin disorders of the musculoskeletal and nervous systems as result of a chronic overuse injury to the affected tissues (Putz-Anderson, 1988).

The several current methods for ergonomic assessment of risk from work and at workplaces aim in general to identify and quantify the overall exposure, rather than the actual risk itself. Risk (i.e., the probability of an unfavourable outcome multiplied by the consequence in general terms) can be quantified as the number of cases per year, annual cost of compensation for sick leave or in some other manner. Since dose-response relationships are difficult to establish and therefore often not available, assessment of exposure alone is considered acceptable. The relationship between exposure and response is often considered to be linear and threshold levels for no risk or levels for acceptable risk are expressed in terms of the level of exposure.

Assessment of exposure commonly involves (in order of increasing precision): subjective judgments, systematic observations and/or direct (or technical) measurements (David, 2005; Burdorf and Van Der Beek, 1999; Kuorinka et al., 1995).

Subjective judgments typically consist of exposure self-reported by workers in the form of diaries, interviews or questionnaires, can apparently be applied in a straightforward manner, and can be obtained for a wide range of working situations at relatively low cost (Silverstein et al., 1997). However, a major disadvantage is that such perceptions by workers have proven to be imprecise and unreliable (Spielholz et al., 2001; Hansson et al., 2001).

Systematic observations (Takala et al., 2010), either direct or indirect by video recording, usually focus on aspects of the work of one individual and are evaluated systematically according to method-specific ergonomic criteria. This type of method is primarily postural-oriented focusing on static exposure, although in some cases self-ratings by the worker observed (e.g., perceived exertion), are included to a certain extent. The easy accessibility and uncomplicated nature of such observations make them affordable, although the requirement for skilled observers and adequate time, might influence cost effectiveness (Juul-Kristensen et al., 2001; Li and Buckle, 1999; Burdorf and Van Der Beek, 1999; Spielholz et al., 2001).

Direct measurement of movements and physical exertion during work can provide objective data of considerable precision. Typically, devices such as goniometers and inclinometers are attached to the worker to record data over a period of time, allowing analysis of exposure to both static and dynamic biomechanical variables. In recent years, such devices have become both inexpensive and easy to use (Dahlqvist et al., 2016) and the cost-effectiveness of inclinometers shown to be similar to that of an observational method (Trask et al., 2014).

Computerisation has led to the development of tools for digital human modelling (DHM) that simulate and visualise work, allowing testing and comparison of alternative workstation designs (Lämkull et al., 2008). Accordingly, proactive ergonomic efforts at an early stage in development of the product or production process has become feasible (Chaffin, 2005; Chang and Wang, 2007; Zhang and Chaffin, 2005; Woldstad, 2000; Sundin and Örtengren, 2006). Such DHM tools for proactive ergonomic risk evaluation of biomechanical load often include procedures for observational assessment of posture, such as RULA (McAtamney and Corlett, 1993) and OWAS (Karhu et al., 1977). Some [e.g., Delmia Human (http://www.delmia.com) and EMA (Fritzsche et al., 2012)] have also implemented more comprehensive observational methods of assessment such as OCRA (Occhipinti, 1998) and EAWS (Schaub et al., 2013), which take key time-dependent variables of exposure (such as repetitive actions and duration) into consideration to a greater extent.

However, in observational methods, the exposure to different risk factors are subjectively rated into a few categories by the observer. This results in relatively rough ratings that often have a low reliability and are too unspecific to allow evaluation of minor ergonomic changes. Moreover, the assessed risks of different methods may differ considerably (Kjellberg et al., 2015; Chiasson et al., 2012). Recently, Forsman (2017) showed that the reliability of six observational assessment methods concerning postures, movements and forces, was only slightly better than chance, concluding that reliable assessments requires complementary direct measurements.

Although observational methods are, as mentioned, being incorporated into DHM tools and may contribute to preventing WMSDs, such methods do not fully utilise the capabilities of DHM tools to rapidly provide large amounts of detailed data concerning kinematics, posture, motion and physical workload. However, much information obtained by direct measurement, such as joint angles, can also easily be obtained with DHM tools. Thus, direct measurement strategies could advantageously be used to quantify physical exposure in DHM tools, which could be seen as a complement to perform DHM exposure assessments (Marras et al., 2010b, 2010a, Lindegård et al., 2003). Moreover, the increased real-life direct measurements of physical exposure (Forsman, 2017) calls for the possibility to perform comparable virtual assessments using DHM. Hence, DHM tools should enable exposure calculations in the same or similar ways as used when analysing direct measurement data from postures and motions in the real world. Thereby, it would be possible to draw similar conclusions on the risks for WMSDs as when real-life direct measurements are used. In addition, it would be advantageous to use exposure-response relationships obtained utilising direct measurements in epidemiological studies to assess the risks for WMSDs. But knowledge of relationships between mechanical exposure and musculoskeletal disorders remains limited. Such relationships are needed to enable assessment of risks for WMSDs from exposure data. However, wrist complaints and disorders within different occupational sectors have in recent years been closely studied with respect to work exposures. Direct measurement methods such as electro-goniometers, electromyography and data-loggers have been employed to measure wrist posture, wrist extensor muscular activity and variables of wrist movement (e.g., angular velocity and repetitivity) for half a day. At the same time, complaints and diagnoses involving the wrist and forearm were assessed by self-reports and clinical examinations (Palmerud et al., 2012; Nordander et al., 2008; Stål et al., 2000; Juul-Kristensen et al., 2002) and exposure-response relationships established (Nordander et al., 2013). Relationships of this kind should be utilised in connection with DHM software to perform risk assessments.

The purpose of this paper is to describe the application of motion data obtained from computer manikin simulations of work procedures, calculation of exposure and comparison with reference data and epidemiological studies of ergonomic risk assessment. In addition, the approach developed is illustrated by predicting the prevalence of work-related hand/wrist disorders in connection with virtual verification of a task involved in vehicle assembly.

2 Materials and methods

First, a literature survey was performed in order to establish a database concerning associations between directly measured exposure of the wrist and musculoskeletal response in connection with various occupations and work situations. This survey was conducted primarily in databases such as PubMed, Scopus, Google Scholar and ScienceDirect with key search terms (alone or in combination) such as wrist assessment, upper limb biomechanical exposure, ergonomic assessment, exposure-response relationship, WMSDs, ergonomic evaluation, epidemiological studies and physical workload. For each relevant publication, the method of measurement, exposure variables selected, occupation studied technical findings and if any exposure-response relationships were noted in order to identify variables of exposure commonly measured directly in attempt to assess physical workload, along with exposure and response data, from different occupations and work situations.

2.1 The test case: assembly of a central electronic module

Assembly of a CEM, a manual task in the assembly of automobiles associated with unfavourable loading of the wrist joint and consequent risk for WMSDs, was selected as a test case and simulated using the DHM tool IMMA [intelligently moving manikin (Högberg et al., 2016; Hanson et al., 2014)].

In the automobile factory, the CEM is put in on the assembly line before the front door and seats. To facilitate this task, the car is elevated to a suitable height. In the task simulated, the operator grasps (usually with his/her right hand) the CEM, usually lying on a table next to the car, and, standing with his/her trunk directed towards the car and left hand on the front side of the car for support, leans inside the car and, with extended arm, places the CEM under the dashboard. The position of the CEM is concealed and the operator has only a limited view of and access to its final location (Figure 1). This part of the task takes approximately 7.5 s, after which the worker removes dummy plugs from and connects cables to the CEM. When the task is finished, the worker returns to a resting neutral standing position. The overall task time, approximately 70 seconds, which is equal to the cycle time (i.e., the balance time) of the assembly line, ends when the operator is just about to start a following task.

Figure 1 The three consecutive moments of the early stage of the CEM assembly (see online version for colours)

The IMMA tool simulates the body postures and motions required to perform the task by assigning joint angles to the internal model of a manikin's skeleton utilising advanced path planning and optimisation (Bohlin et al., 2012; Delfs et al., 2013), replicating the pattern of human performance. In this simulation, timing of the task is based on the specifications in the worker's instruction sheet. This simulation was repeated for each member of the family of manikins representing the anthropometric diversity among the work force, i.e., five male manikins (weight 51–103 kg, stature 1,658–1,925 mm) and five female manikins (weight 44–85 kg, stature 1,548–1,798 mm).

After simulation of the assembly task, the flexion-extension and ulnar-radial deviation angles of the right wrist joint were analysed with the dynamic wrist exposure module of the IMMA tool. The risk for any musculoskeletal disorder was predicted using a user interface, here in Excel. The exposure module computed the wrist angle at 25 Hz to create time curves (of the wrist angles) during the initial 7.5 s of assembly. For analysis of risk exposure, these time curves were exported to Excel and used to calculate velocity, the mean power frequency (MPF, the centre of gravity of the power spectrum) and motion pauses.

The wrist angle was determined as the angle between one line in the centre of the palm and another line in the centre of the lower arm and designed as positive for flexion and ulnar deviation and negative for extension and radial deviation.

3 Results

3.1 Selection of exposure variables

Based on the results of the literature survey, four risk factors for arm and wrists related disorders: *posture*, *velocity*, *repetitive motion* and *lack of motion pause*, were selected for quantification, for the reasons given below.

3.1.1 Posture

Of all hand-arm disorders, most attention has been focused on the carpal tunnel syndrome (CTS), which involves the median nerve (Putz-Anderson, 1988) in the carpal tunnel. Working with the wrist in a non-neutral posture was associated early on with an elevated incidence of CTS (Armstrong and Chaffin, 1979) and this relationship later confirmed (Morgenstern et al., 1991; De Krom et al., 1990; Nordstrom et al., 1997; Andersen et al., 2003; Blanc et al., 1996; Spahn et al., 2012; You et al., 2014). Investigations both on cadavers (Keir et al., 1997) and in vivo (Weiss et al., 1995) have revealed a parabolic relationship between wrist posture and carpal tunnel pressure, with elevated pressure being associated with wide wrist angles, especially during flexion and extension and less so in connection with ulnar-radial deviation.

Elevated pressure in the carpal tunnel can restrict blood flow to the nerves, as well as damaging the nerve sheaths, which may lead to symptoms such as pain, numbness and tingling in the fingers innervated by the median nerve. Nerve entrapment could affect the ulnar nerve at the wrist (Guyon's canal syndrome) or at the elbow (Cubital tunnel syndrome). Entrapment affecting the radial nerve (Radial tunnel syndrome) is experienced as soreness at the lateral part of the elbow and can resemble sensations of lateral epicondylitis. Furthermore, certain epidemiological evidence suggests that working with non-neutral wrist postures, especially in combination with forceful or repetitive activities, contributes to lateral and medial epicondylitis (Haahr and Andersen, 2003; Putz-Anderson, 1988; Leclerc et al., 2001; Fan et al., 2009). Accordingly, the flexion-extension and ulnar-radial deviation angles of the wrist are suitable (kinematic) measures of exposure.

3.1.2 Velocity

Variables such as the angular velocity and acceleration of the wrist, particularly in connection with flexion-extension, differ in a distinct manner between occupational groups with low and high incidences of cumulative trauma disorders (CTD) (Schoenmarklin and Marras, 1993; Marras and Schoenmarklin, 1993; Schoenmarklin et al., 1994; Nordander et al., 2013; Heilskov-Hansen et al., 2016). Both of these variables are suitable for quantification, but since measurement of acceleration is more sensitive to disturbance by high-frequency noise, only angular velocity was considered here.

3.1.3 Repetitive motions

Repetitive tasks involving high-speed hand-arm motions and short cycles [defined as a cycle time < 10 seconds or performance of the same movements > 50% of the cycle time (Silverstein et al., 1986)] are well documented risk factors for disorders of the wrist, hand and elbow (Latko et al., 1999; Palmer, 2003; Van Rijn et al., 2009; Roquelaure et al., 1997). In several studies, highly repetitive wrist movements have been associated with the highest risk of developing CTS (Silverstein et al., 1987; Spahn et al., 2012; Palmer et al., 2007; Van Rijn et al., 2009; Hansson et al., 2000). This situation may be explained by increased pressure within the fixed volume of the carpal tunnel due to swelling of the synovial sheath surrounding the flexor tendons. Frequent or repeated movements may also result in e.g., tendinitis and tenosynovitis, i.e., inflammation and sheet injury to muscle tendons (Rempel et al., 1999). For instance, De Quervains's disease, involving inflammation of the sheaths of thumb tendons that extend over the wrist and extend the thumb joints, is usually accompanied by e.g., painfulness along the back of the thumb and difficulty and painfulness in moving the thumb/wrist (Moore, 1997). Medial ('golf elbow') and lateral epicondylitis ('tennis elbow') involve irritation of the attachment of the tendon of the finger flexor or extensor muscle to the epicondyles of the elbow, causing, e.g., pain along the forearm in connection with wrist flexion or extension and impairing grip (strength). Thus, quantification of repetitiveness or periodicity of movements is a suitable measure of exposure.

3.1.4 Motion pause

The opportunity of muscles to rest is of crucial importance in connection with WMSDs (Mital et al., 2000; Veiersted et al., 1993). For instance, adequate recovery time relieves pressure within the carpal tunnel, thereby helping to avoid injury (Cheever et al., 1995). Velocity exerts a significant impact on CTD, so the proportion of time with little or no angular velocity is also of interest. Motion pauses (i.e., time in a neutral posture with low velocity) are used as indicators of periods of muscle 'rest' instead of gaps in electromyography (Palmerud et al., 2012). Since work including few such gaps promotes future development of WMSDs (Veiersted et al., 1993), quantification of motion pauses is also a suitable measure of exposure.

3.1.5 Effects of combined exposure

Since several risk factors are often present concurrently, potential synergistic effects must be considered. In fact, the more extensive the combination of risk factors, the higher the risk of acquiring a disorder (Palmer, 2011; Van Rijn et al., 2009; Giersiepen and Spallek, 2011; Gallagher and Heberger, 2013). However, it is not clear, how such combination effects should be assessed and, therefore, these are not taken into consideration here.

3.2 Calculation of exposure measures

Sensors attached directly to the body, can provide precise and continuous monitoring of exposure during a period of time. Digitised values for further processing can be obtained from the sensor output, where a sampling rate of 20 Hz has shown to be suitable (Hansson et al., 1996). Corresponding values can also be obtained from computer simulations of work, using manikins as operators. Wrist postures and angular velocities can be described effectively with the amplitude probability function (Balogh et al., 2009; Kazmierczak et al., 2005; Wahlström et al., 2010; Jonker et al., 2009; Åkesson et al., 1997; Juul-Kristensen et al., 2001). The 5th, 10th, 50th, 90th and 95th percentile values are commonly used to describe the posture and angular velocity of a joint in each plane of movement.

With the angle and sign convention given above, the 10th percentile for flexion denotes the peak angle for extension, while the 90th percentile denotes peak flexion. Similarly, the 10th percentile for deviation denotes the peak angle for radial deviation, and the 90th percentile denotes peak ulnar deviation. Here, movements were characterised by their absolute angular velocities, where the 10th percentile denotes low, the 50th percentile median and the 90th percentile peak velocity. For clarification, the 10th percentile posture denotes measured angles below this value during 10% of the time and above this value 90% of the time. Correspondingly, the 50th percentile posture represents angles that are below this value half of the time and half time above, and the 90th percentile posture signifies angles above this value 10% of the time. The 10th percentile velocity denotes that the velocities are below this value during 10% of the time, 50th percentile velocity denotes velocities that are below this value half of the time and half time above, 90th percentile velocity denotes velocities above this value 10% of the time.

For quantification of work repetitiveness, the MPF is more relevant than cycle time (Hansson et al., 1996). Moreover, the MPF [in Hz or in cycles per minute (Radwin and Lin, 1993; Radwin et al., 1994; Balogh et al., 2009; Mann et al., 1989; Hansson et al., 1996; Arvidsson et al., 2003)] can differentiate between apparently similar work tasks (Ohlsson et al., 1994). Here, the MPF values for wrist angular flexion-extension and ulnar-radial deviation of the wrist were obtained by fast Fourier transform (FFT) in order to compute the power spectrum of these angles during the entire duration of the task (for further details, see, e.g., Hansson et al. (1996). Motion pause can be defined in different ways. A common definition of when the hand is being held still is when the wrist joint exhibits an angular velocity of < 1 °/s in a sequence of at least 0.5 s (Balogh et al., 2009; Thomsen et al., 2002). In the present case, a function in MATLAB was developed to calculate the percentage of motion pause according to this definition.

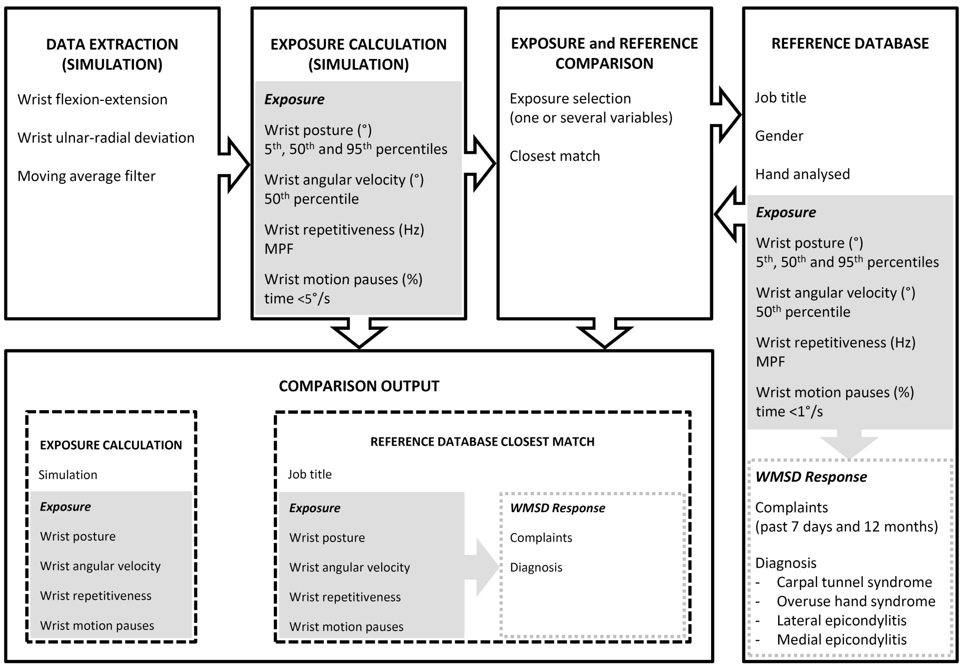
3.3 The reference data

The literature survey provided a reference database summarising available epidemiological exposure and response data for the wrist (Tables 1 and 2). Table 1 documents the articles included, occupations involved, work tasks analysed, worker gender and wrist joint exposure. The exposure is characterised in terms of group mean values of 10th, 50th and 90th percentile for flexion-extension and ulnar-radial deviation angles of the wrist, the 50th percentile for the absolute angular velocity of flexion-extension and ulnar-radial deviation, MPF and motion pause. These variables discriminate between the exposure of different occupational groups most effectively and are therefore recommended for use in field studies (Hansson et al., 2009). Table 2 presents the prevalence of complaints and diagnoses of WMSDs among the same occupational groups as in Table 1. For each group, the percentage of workers who made such complaints during the past 7 days or 12 months and, when available, diagnoses and the percentage with the diagnosed disorders, are reported.

3.4 Ergonomic risk assessment

A principal outline for ergonomic risk assessment employing DHM tools was developed. This approach involves direct measurement of exposure and reference exposure data for a number of occupational tasks (Table 1), along with epidemiological data concerning WMSDs associated with these same occupational tasks (Table 2). The principal steps of the assessment of risk for WMSDs in the wrist is illustrated in Figure 2 and these steps are described further in the following sections. The wrist is used in the test case, but the same approach can be applied to other parts of the body.

Figure 2 Risk assessment flowchart



3.4.1 Data extraction

In the DHM tool, motions of the manikin are generated by inverse kinematics with a comfort function seeking to optimise comfort while maintaining a collision-free path for the body part. The time resolution corresponds to a sampling frequency of 25 Hz. Digitised time curves of the flexion-extension and ulnar-radial deviation angle of the wrist are extracted for subsequent calculation of the exposure variables.

Table 1 Exposure variables of the dominant (D) and non-dominant (ND) wrist of males (M) and females (F) in various occupational tasks

Reference	*Work task*	*Wrist*	*Sex*	*Flexion-extension*						*Ulnar-radial deviation*					
				Posture[a] °			*Velocity* °/s	*Repetitivity motion/min*	*Motion pause*[b]	*Posture*[a] °			*Velocity* °/s	*Repetitivity motion/min*	*Motion pause*[b]
				Percentile			*Percentile*	*MPF*	*< 1 °/s*	*Percentile*			*Percentile*	*MPF*	*< 1 °/s*
				10th	*50th*	*90th*	*50th*	*(Hz)*	*(%)*	*10th*	*50th*	*90th*	*50th*	*(Hz)*	*(%)*
Arvidsson et al. (2003)	Producing earplugs	D	F	–21	–2	14	29	0.53	1.4	–3	9	18	20	0.62	2.1
Arvidsson et al. (2003)	Producing earplugs	ND	F	–26	–3	13	25	0.4	1.1	–5	7	17	17	0.48	1.7
Arvidsson et al. (2006)	Air traffic control	D	M	–37	–19	–1	2.5	-	20	–8	2	12	-	-	20
Arvidsson et al. (2006)	Air traffic control	ND	M	–28	–11	2	-	-	21	–8	3	13	-	-	25
Arvidsson et al. (2006)	Air traffic control	D	F	–44	–28	–4	2.9	-	17	–8	2	11	-	-	22
Arvidsson et al. (2006)	Air traffic control	ND	F	–28	–7	10	-	-	20	–6	6	16	-	-	27
Arvidsson et al. (2012)	Meat cutting	D	M	–36	–9	17	38	-	0.7	-	-	-	-	-	-
Balogh et al. (2006)	Manual parquet slats sorting	D	F	–39	–18	7	22	0.4	3	-	-	-	-	-	-
Balogh et al. (2006)	Semi-automated parquet slats sorting	D	F	–31	–10	7	5	0.33	10	-	-	-	-	-	-
Balogh et al. (2006)	Automated Parquet slats sorting	D	F	–38	–6	20	12	0.27	7	-	-	-	-	-	-
Chen et al. (2010)	Hair dressing	D	F, M	–42	–14	18	-	-	-	–7	9	27	-	-	-
Chen et al. (2010)	Hair dressing	ND	F, M	–36	–7	26	-	-	-	-8	7	23	-	-	-

Notes: [a]Positive values denotes palmar flexion and ulnar deviation.
[b]Angular velocity <1°/s in a sequence of at least 0.5 s.

Table 1 Exposure variables of the dominant (D) and non-dominant (ND) wrist of males (M) and females (F) in various occupational tasks (continued)

Reference	*Work task*	*Wrist*	*Sex*	*Flexion-extension*						*Ulnar-radial deviation*					
				Posture[a]°			*Velocity °/s*	*Repetitivity motion/min*	*Motion pause*[b]	*Posture*[a]°			*Velocity °/s*	*Repetitivity motion/min*	*Motion pause*[b]
				Percentile			*Percentile*	*MPF*	*< 1 °/s*	*Percentile*			*Percentile*	*MPF*	*< 1 °/s*
				10th	*50th*	*90th*	*50th*	*(Hz)*	*(%)*	*10th*	*50th*	*90th*	*50th*	*(Hz)*	*(%)*
Hansson et al. (2000)	Laminate production	D	F	–45	–21	3	23	0.42	5.4	-	-	-	-	-	-
Hansson et al. (2000)	Laminate production	ND	F	–46	–23	0	21	0.41	4.9	-	-	-	-	-	-
Hansson et al. (2000)	Varied industrial work	D	F	–42	–17	10	19	0.31	7.4	-	-	-	-	-	-
Hansson et al. (2000)	Varied industrial work	ND	F	–38	–14	10	13	0.27	12	-	-	-	-	-	-
Hansson et al. (2000)	Varied office work	D	F	–46	–30	-4	10	0.26	17	-	-	-	-	-	-
Hansson et al. (2000)	Varied office work	ND	F	–54	–30	4	3	0.19	34	-	-	-	-	-	-
Heilskov-Hansen et al. (2016)	Painting	D	M	–48	–20	7	14.5	0.27	-	–15	1	18	9	0.28	-
Heilskov-Hansen et al. (2016)	Painting	D	F	–50	–22	7	14.6	0.27	-	–19	–2	14	9.2	0.28	-
Jensen et al. (1998)	CAD work with mouse	D	F, M	15	26	34	2	-	28	4	14	21	2	-	31
Nordander et al. (2008)	Assembly: producing brake regulators	D	F	–40	–13	12	19	-	-	-	-	-	-	-	-

Notes: [a]Positive values denotes palmar flexion and ulnar deviation.
[b]Angular velocity <1°/s in a sequence of at least 0.5 s.

Table 1 Exposure variables of the dominant (D) and non-dominant (ND) wrist of males (M) and females (F) in various occupational tasks (continued)

Reference	Work task	Wrist	Sex	*Flexion-extension*						*Ulnar-radial deviation*					
				Posture[a]°			*Velocity °/s*	*Repetitivity motion/min*	*Motion pause*[b]	*Posture*[a]°			*Velocity °/s*	*Repetitivity motion/min*	*Motion pause*[b]
				Percentile			*Percentile*	*MPF*	*< 1 °/s*	*Percentile*			*Percentile*	*MPF*	*< 1 °/s*
				*10*th	*50*th	*90*th	*50*th	*(Hz)*	*(%)*	*10*th	*50*th	*90*th	*50*th	*(Hz)*	*(%)*
Nordander et al. (2008)	Assembly: producing brake regulators	D	M	–38	–10	14	18	-	-	-	-	-	-	-	-
Nordander et al. (2008)	Producing rubber-sealing	D	F	–35	–8	19	23	-	-	-	-	-	-	-	-
Nordander et al. (2008)	Producing rubber-sealing	D	M	–36	–8	12	16	-	-				-	-	-
Nordander et al. (2013)	Hairdressing	D	F	–44	14	21	20	-	-	-	-	-	-	-	-
Nordander et al. (2013)	Day nursery work	D	F	–40	–6	24	11	-	-	-	-	-	-	-	-
Nordander et al. (2013)	Caretaker work	D	M	–35	–10	19	17	-	-	-	-	-	-	-	-
Nordander et al. (2013)	Data entry: Giro form	D	F	–40	–28	–11	26	-	-	-	-	-	-	-	-
Nordander et al. (2013)	Information service	D	F	–]44	–29	–8	2.2	-	-	-	-	-	-	-	-
Nordander et al. (2013)	Partly VDU work	D	F	–41	20	8	6.1	-	-	-	-	-	-	-	-
Nordander et al. (2013)	Partly VDU work	D	M	–39	–17	11	3.5		-	-	-	-	-	-	
Ohlsson et al. (1994)	Fish processing	D	F	-	–1	-	41	0.54	0.6	-	-	-	-	-	-
Ohlsson et al. (1994)	Fish processing	D	M	–33	–6	14	25			-	-	-	-	-	-
Thomsen et al. (2002)	Repetitive work: data entry	D	F, M	–39	-	–17	23	0.68	2.2	-	-	-	-	-	-

Notes: [a]Positive values denotes palmar flexion and ulnar deviation.
[b]Angular velocity <1°/s in a sequence of at least 0.5 s.

Table 1 Exposure variables of the dominant (D) and non-dominant (ND) wrist of males (M) and females (F) in various occupational tasks (continued)

Reference	*Work task*	*Wrist*	*Sex*	*Flexion-extension*						*Ulnar-radial deviation*					
				Posture[a]°			*Velocity* °/s	*Repetitivity motion/min*	*Motion pause*[b]	*Posture*[a]°			*Velocity* °/s	*Repetitivity motion/min*	*Motion pause*[b]
				Percentile			*Percentile*	*MPF*	< 1 °/s	*Percentile*			*Percentile*	*MPF*	< 1 °/s
				10th	*50th*	*90th*	*50th*	(*Hz*)	(%)	*10th*	*50th*	*90th*	*50th*	(*Hz*)	(%)
Thomsen et al. (2002)	Repetitive work: data entry	ND	F, M	–38	-	–17	3	0.26	53.3	-	-	-	-	-	-
Thomsen et al. (2002)	Forceful and repetitive: sorting parcels	D	F, M	–36	-	31	41	0.59	0.9	-	-	-	-	-	-
Thomsen et al. (2002)	Forceful and repetitive: sorting parcels	ND	F, M	–35	-	14	28	0.47	2	-	-	-	-	-	-
Thomsen et al. (2002)	Forceful: automatic letter sorting	D	F, M	–38	-	19	25	0.32	3.7	-	-	-	-	-	-
Thomsen et al. (2002)	Forceful: automatic letter sorting	ND	F, M	–46	-	12	27	0.37	3.7	-	-	-	-	-	-
Thomsen et al. (2002)	Varied work: office work	D	F, M	–34	-	-6	6	0.23	21.5	-	-	-	-	-	-
Thomsen et al. (2002)	Varied work: office work	ND	F, M	–31	-	-6	0	0.27	48.9	-	-	-	-	-	-
Unge et al. (2007)	Cleaning: extended organisation	D	F	–36	–5	24	20	0.33	3.8	-	-	-	-	-	-

Notes: [a]Positive values denotes palmar flexion and ulnar deviation.
[b]Angular velocity <1°/s in a sequence of at least 0.5 s.

Table 1 Exposure variables of the dominant (D) and non-dominant (ND) wrist of males (M) and females (F) in various occupational tasks (continued)

Reference	Work task	Wrist	Sex	*Flexion-extension*						*Ulnar-radial deviation*					
				Posture[a]°			*Velocity* °/s	*Repetitivity motion/min*	*Motion pause*[b]	*Posture*[a]°			*Velocity* °/s	*Repetitivity motion/min*	*Motion pause*[b]
				Percentile			*Percentile*	*MPF*	< 1 °/s	*Percentile*			*Percentile*	*MPF*	< 1 °/s
				10th	*50th*	*90th*	*50th*	(*Hz*)	(%)	*10th*	*50th*	*90th*	*50th*	(*Hz*)	(%)
Unge et al. (2007)	Cleaning: traditional organisation	D	F	–35	–5	24	28	0.38	1.4	-	-	-	-	-	-
Åkesson et al. (1997)	Dental work including drilling	D	F	–42	–21	7	6.2	0.18	18	–14	–2	12	2.7	0.20	27
Åkesson et al. (1997)	Dental work including drilling	ND	F	–27	3	12	1.5	-	36	–6	12	31	0.7	0.14	41
Åkesson et al. (2012)	Dental hygienists	D	F	–45	–17	13	7.3	-	-	-	-	-	-	-	-
Åkesson et al. (2012)	Dental hygienists	ND	F	–36	–11	13	2.4	-	-	-	-	-	-	-	-

Notes: [a]Positive values denotes palmar flexion and ulnar deviation.
[b]Angular velocity <1°/s in a sequence of at least 0.5 s.

Table 2 WMSDs among the same groups characterised in Table 1: complaints, when available, during the past 12-month and 7 days and, when available, diagnoses for the past 7 days

Reference	*Work task*	*Sex*	*Wrist*	*Complaints (%)*		*Diagnoses (%)*				
				12 months	*7 days*	*One or more*	*Lateral epicondylitis*	*Medial epicondylitis*	*Carpal tunnel syndrome*	*Overuse hand syndrome*
Arvidsson et al. (2003)	Producing earplugs	D	F	70	–	67	–	–	–	–
Arvidsson et al. (2003)	Producing earplugs	ND	F	"	–	24	–	–	–	–
Arvidsson et al. (2006)	Air traffic control	D	M	30	11	2	2	0	0	0
Arvidsson et al. (2006)	Air traffic control	ND	M	"	11	2	2	0	0	0
Arvidsson et al. (2006)	Air traffic control	D	F	28	17	3	1	1	1	0
Arvidsson et al. (2006)	Air traffic control	ND	F	"	17	3	1	1	1	0
Arvidsson et al. (2012)	Meat cutting	D	M	66	38	14	0	4	11	2
Balogh et al. (2006)	Manual parquet slats sorting	D	F	52	30	7	5	3	1	0
Balogh et al. (2006)	Semi-automated parquet slats sorting	D	F	"	30	7	5	3	1	0
Balogh et al. (2006)	Automated Parquet slats sorting	D	F	"	30	7	5	3	1	0
Chen et al. (2010)	Hair dressing	D	F, M	50	–	–	–	–	–	–
Chen et al. (2010)	Hair dressing	ND	F, M	"	–	–	–	–	–	–
Hansson et al. (2000)	Laminate production	D	F	51	30	47	0	0	0	1
Hansson et al. (2000)	Laminate production	ND	F	"	35	45	5	0	0	0
Hansson et al. (2000)	Varied industrial work	D	F	29	17	26	0	0	0	0
Hansson et al. (2000)	Varied industrial work	ND	F	"	11	14	0	0	0	0
Hansson et al. (2000)	Varied office work	D	F	33	9	18	3	0	0	0
Hansson et al. (2000)	Varied office work	ND	F	"	9	21	0	0	0	0

Notes: D: Dominant wrist and ND: Non-dominant wrist.
M: Males and F: Females.

Table 2 WMSDs among the same groups characterised in Table 1: complaints, when available, during the past 12-month and 7 days and, when available, diagnoses for the past 7 days (continued)

Reference	*Work task*	*Sex*	*Wrist*	*Complaints (%)*		*Diagnoses (%)*				
				12 months	*7 days*	*One or more*	*Lateral epicondylitis*	*Medial epicondylitis*	*Carpal tunnel syndrome*	*Overuse hand syndrome*
Heilskov-Hansen et al. (2016)	Painting	D	M	–	–	–	–	–	1.5	–
Heilskov-Hansen et al. (2016)	Painting	D	F	–	–	–	–	–	3.3	–
Jensen et al. (1998)	CAD work with mouse	D	F, M	52	19	–	–	–	–	–
Nordander et al. (2008)	Assembly: producing brake regulators	D	F	71	54	20	6	3	10	2
Nordander et al. (2008)	Assembly: producing brake regulators	D	M	60	31	6	3	1	4	0
Nordander et al. (2008)	Producing rubber-sealing	D	F	59	43	6	1	0	2	0
Nordander et al. (2008)	Producing rubber-sealing	D	M	41	30	0	0	0	0	0
Nordander et al. (2013)	Hairdressing	D	F	49	33	9	1	0	6	0
Nordander et al. (2013)	Daily nursery work	D	F	34	26	4	2	2	2	1
Nordander et al. (2013)	Caretaker work	D	M	28	16	2	1	1	0	0
Nordander et al. (2013)	Data entry: giro form	D	F	47	29	–	–	–	–	–
Nordander et al. (2013)	Information service	D	F	7	4	–	–	–	–	–
Nordander et al. (2013)	Partly VDU work	D	F	38	23	5	2	0	2	0
Nordander et al. (2013)	Partly VDU work	D	M	20	12	2	2	0	0	0
Ohlsson et al. (1994)	Fish processing	D	F	57	40	15	1	2	9	1
Ohlsson et al. (1994)	Fish processing	D	M	30	19	4	2	3	1	0
Thomsen et al. (2002)	Repetitive work: data entry	D	F,M	–	23	–	–	–	4	–

Notes: D: Dominant wrist and ND: Non-dominant wrist.
M: Males and F: Females.

Table 2 WMSDs among the same groups characterised in Table 1: complaints, when available, during the past 12-month and 7 days and, when available, diagnoses for the past 7 days (continued)

Reference	*Work task*	*Sex*	*Wrist*	*Complaints (%)*		*Diagnoses (%)*				
				12 months	*7 days*	*One or more*	*Lateral epicondylitis*	*Medial epicondylitis*	*Carpal tunnel syndrome*	*Overuse hand syndrome*
Thomsen et al. (2002)	Repetitive work: data entry	ND	F,M	–	17	–	–	–	0	–
Thomsen et al. (2002)	Forceful & repetitive: sorting parcels	D	F,M	–	4	–	–	–	1	–
Thomsen et al. (2002)	Forceful and repetitive: sorting parcels	ND	F,M	–	3	–	–	–	0	–
Thomsen et al. (2002)	Forceful: automatic letter sorting	D	F,M	–	9	–	–	–	1	–
Thomsen et al. (2002)	Forceful: automatic letter sorting	ND	F,M	–	8	–	–	–	1	–
Thomsen et al. (2002)	Varied work: office work	D	F,M	–	20	–	–	–	0	–
Thomsen et al. (2002)	Varied work: office work	ND	F,M	–	11	–	–	–	0	–
Unge et al. (2007)	Cleaning: extended organisation	D	F	55	35	13	4	2	7	1
Unge et al. (2007)	Cleaning: traditional organisation	D	F	68	46	20	7	2	8	4
Åkesson et al. (1997)	Dental hygienists	D	F	55	41	14	0	2	10	4
Åkesson et al. (1997)	Dental hygienists	ND	F	“	41	14	0	2	10	4
Åkesson et al. (2012)	Dental work including drilling	D	F	42	24	–	–	–	–	–
Åkesson et al. (2012)	Dental work including drilling	ND	F	“	24	–	–	–	–	–

Notes: D: Dominant wrist and ND: Non-dominant wrist.
M: Males and F: Females.

3.4.2 Exposure calculation

Exposure data [here filtered and re-sampled to 20 Hz in MATLAB using a low-pass filter with a cut-off filter of 5 Hz (Hansson et al., 1996)] involve flexion-extension and ulnar-radial deviation of the wrist joint that are considered separately. The 10th, 50th and 90th percentiles of posture, as well as the 50th percentile of absolute angular velocity are calculated together with the MPF and the time percentage with motion pauses. When a manikin family is used, the mean values of exposure for the entire family are representing the exposure. A function in the program allows saving the calculated exposures in a separate part of the reference database.

3.4.3 Exposure and reference comparison

Measures of exposure can be compared with the corresponding reference values in the database (Table 1), either individually or in combination. An algorithm has been developed for multiple comparisons, but for simplicity, here the exposure variables are compared one by one. The best matches are identified automatically and are presented together with the corresponding percentages of workers with wrist complaints in these occupational groups in Table 2.

3.4.5 Comparison output

Hence, each exposure variable is presented together with the corresponding value, the occupation name and the WMSD response of the closest job.

3.5 The test case: CEM assembly

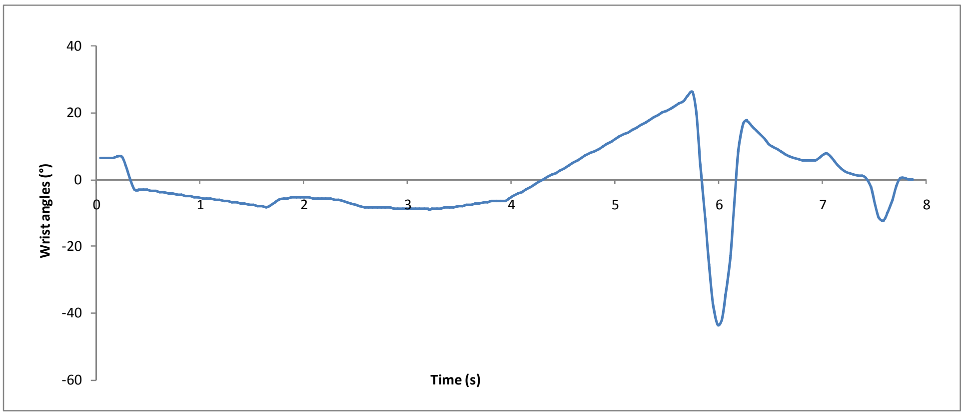
In the simulation of the assembly task by the DHM tool IMMA, the variables of exposure listed below, involving the flexion-extension angle of the right wrist, were quantified for each member of the manikin family (five males and five females) and mean values calculated. The 90th percentile flexion-extension was 25°, the 50th percentile of the absolute angular velocity 10.3 °/s, the MPF of the flexion-extension angle was 0.58 Hz, and the motion pause less than 0.05% of the simulation time, i.e., virtually non-existent.

Figures 3 and 4 depict time curves for the simulation of wrist flexion-extension and angular velocity, respectively for one of the manikins. The duration of this task for this manikin was 7.8 seconds.

The distribution (single and cumulative) of the flexion-extension of the right wrist during this assembly, illustrated in Figure 5, reveals that more than 50% of the work time is spent in extension and that extensions of 0–10° are common.

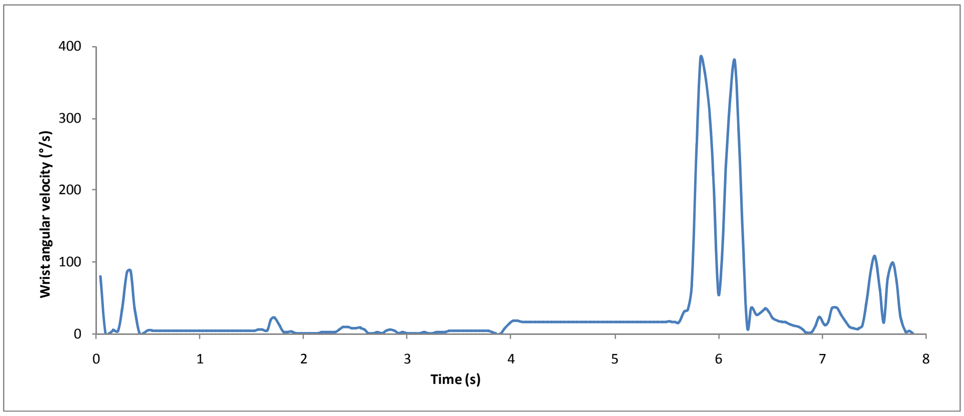
Similarly, the single and cumulative distributions of the absolute angular velocity are illustrated in Figure 6, showing that more than 40% of the velocities are lower or equal to 5 °/s and that more than 80% of the work time is performed at a velocity lower than 20 °/s.

Figure 3 Simulated flexion-extension angles of the right wrist for one manikin performing CEM assembly (see online version for colours)



Note: Negative values denote extension.

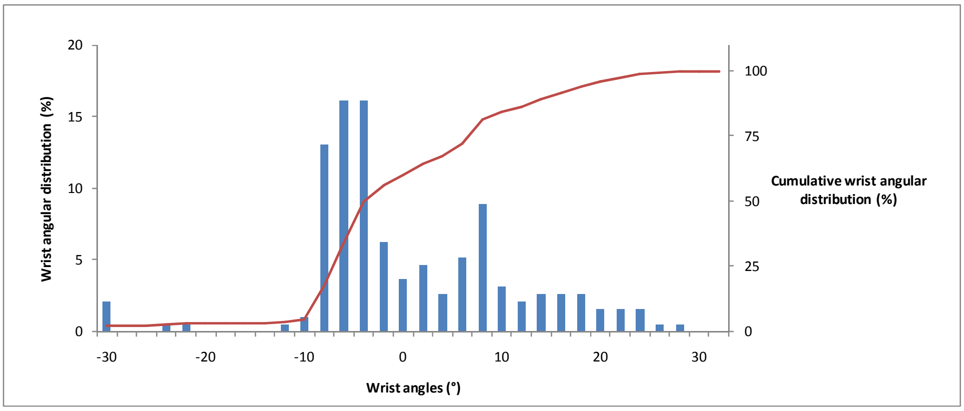
Figure 4 Simulated angular flexion-extension velocity of the right wrist for one manikin performing CEM assembly (see online version for colours)



The simulation also demonstrated a variation in exposure within the manikin family, e.g., the four shortest manikins (representing females) exhibited a wider range of wrist motion as well as slower angular velocity than the taller manikins.

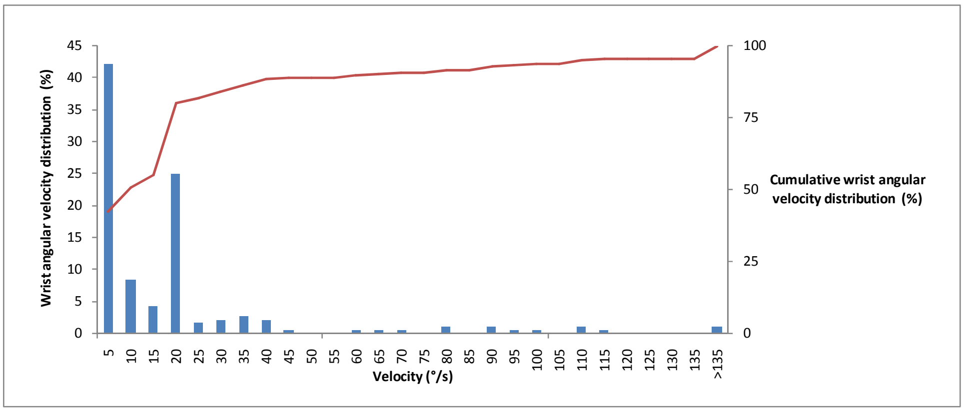
Comparison of the mean exposures of the manikin family during the simulated CEM assembly to the reference data, revealed different best job matches for the different exposure variables. For the 90th percentile of flexion-extension, the best matching occupations were 'cleaning' and 'daily nursery work'; for the 50th percentile angular flexion-extension velocity, the best match was 'varied office work' while the best match with respect to the MPF was 'sorting parcels (both forceful and repetitive)'. On the basis of these best matches and reported complaints during the seven past days (Table 2) as a predictor of the risk for WMSD, 26–46% of the workers with the 90th percentile flexion-extension angle for a longer period of time can be expected to report wrist pain. In addition, 4–20% of these workers are likely to be diagnosed with one or more wrist-related CTDs.

Figure 5 Single and cumulative distributions of the wrist flexion angles depicted in Figure 3 (see online version for colours)



Note: Negative values denote extension.

Figure 6 Single and cumulative distributions of the wrist angular velocities depicted in Figure 4 (see online version for colours)



4 Discussion

This paper describes and illustrates an alternative DHM approach to exposure and risk assessment that incorporates direct measurements of exposure and epidemiological data on the prevalence of WMSDs obtained from the scientific literature. Usage of this approach is exemplified by assessing the prevalence of hand/wrist-related disorders associated with simulation of a work task involved in vehicle assembly.

4.1 Motivation for direct measurement

Today, assessment of workload exposure is based increasingly on direct measurements, in part at least because of improved sensor technology at reduced costs and easy data storage, either on the device itself, or through wireless transmission. This permits long-term monitoring with high reliability (Dahlqvist et al., 2016), discriminating time-variations of the exposure.

Observational methods are also commonly used to assess workload, particularly when surveys and/or fast screening of possible risks are of interest. Such assessments, either direct or through video-recordings, are relatively simple to perform and, although requiring a certain level of competence of the observer, involve no advanced instrumentation. However, observations are less accurate and less reliable then direct measurements (Liv et al., 2012; Hansson et al., 2001; Trask et al., 2017).

DHM tools can simulate the sequences of movement involved in human work tasks, utilising a structural model of the human body (i.e., a computer manikin), with defined e.g., limbs and joints to monitor the trajectories of body parts. Joint angles and angular velocities and accelerations can be assessed and used to monitor exposure and subsequently evaluate the risk for WMSDs. By using the computer simulation in this way, the same information of exposure can be obtained as is done through direct measurements on real workers, and the same type of strategies could advantageously be used to handle and assess the exposure data. In cases where recommendations for threshold values exist, this will lead to objective risk assessments.

4.2 Assessment and presentation of exposure

Direct determination of exposure, either for human subjects or computer-generated manikins, provides large amounts of data which must be reduced to certain characteristic variables. For example, time averages, minimum and maximum values, root-mean-square values and histograms including percentiles of the value variations can be determined for the recorded work time. The exposure variations can also be studied in the frequency domain by power spectrum analysis and calculation of for example MPF, which can show if there is a dominant repetition visible in the workload variations.

Unlike many observational methods, which report overall exposure associated with the task of interest, the present approach assesses individual exposure variables i.e., posture and angular velocity, as well as MPF and motion pause, in accordance with Hagbergs' recommendations concerning assessments in ergonomic epidemiology (Hagberg, 1992; Winkel and Mathiassen, 1994) giving the analysed work an exposure profile, which accurately describes the overall exposure. Here, the exposure profile includes information about the three main dimensions of mechanical exposure, i.e., level, repetitiveness and duration. Presenting overall exposure in this manner as a collection of separate variables might be seen as lacking the combination of these variables into an overall exposure score. However, weighting of various risk factors is difficult (Winkel and Westgaard, 1992), little is known about their relative impacts, and the epidemiological evidence supporting the compilation of an overall exposure score remains limited (Hagberg, 1992). Thus, at present different exposures cannot be combined in a reliable manner.

4.3 Risk levels

In most observational methods, the overall exposure score is typically interpreted through a three to five level colour system using traffic light coding to characterise exposure as risk: red = *high risk/ineligible exposure* (i.e., *all or most workers are at risk of WMSDs*); yellow = *medium risk/the exposure has to be assessed closer* (i.e., *several workers are at risk of WMSDs*); and green = *negligible risk/acceptable exposure* (*few or none of the workers are at risk of WMSDs*) (Armstrong, 2006, Occhipinti, 1998; Karhu et al., 1977; Ferreira et al., 2009; McAtamney and Corlett, 1993). This enables easy and rapid conclusions regarding the ergonomic situation, especially by those with little experience of ergonomics (non-experts). However, since few observational methods have been tested for predictive validity, such colour-coding should be interpreted with caution. In addition, different observational methods combine exposure variables in different ways and may also set different risk levels, thereby arriving at different conclusions for the same work task (Chiasson et al., 2012; Kjellberg et al., 2015).

4.4 The concept of risk

The objective of ergonomic risk assessment is to identify hazardous exposure in the workplace, and to evaluate risks of developing a harm, disorder or injury. In this context, *hazard* refers to the potential source of harm, and *risk* to the likelihood and severity of that harm (ISO 12100:2010, 2010; EU Directive, 1989). However, the term risk is often used (incorrectly) as a synonym for hazard, which does not include the estimation of the likelihood for an undesirable scenario, but rather as a qualitative estimate. To quantify the risk, the undesirable likelihood of an event is estimated and expressed in percentage, e.g., the risk is 20% if 20% of the individuals in an exposed group develop symptoms.

In epidemiology, incidence and prevalence are important measures to describe the impact of an exposure and severity of risk. Incidence refers to the number of new cases during a given time period among a population subjected to a certain level of exposure, i.e., the average risk for developing symptoms. Prevalence in turn, refers to the number of individuals with the symptoms of interest in a population or group subjected to a certain level of exposure and depends on both the incidence and duration of the harm, and can be used to express the risk of harm in an exposed group.

In the approach presented here, the database of exposure (Table 1) and prevalence data of wrist-related WMSD in different occupational groups is one common way of describing exposure-response relationships. It should be remembered, however, that cross-sectional studies such as those employed to create the database presented, cannot demonstrate a causal relationship because of the absence of temporal-association, nor is the increase in WMSD compared to non-exposed workers (relative risk) documented.

4.5 Interpretation of exposure and its limitations

Tables 1 and 2 summarise data on exposure and outcome from a number of investigations, but give no indication of risk limits. For interpretation of direct measurements of exposure, action limits for the upper limb recommended recently (Hansson et al., 2016) can be utilised. These limits are based on associations between physical exposure (assessed by direct measurement) and health outcome and indicate the risk for injury if the limits are exceeded with respect to either level and/or duration.

In contrast to observational methods with their relatively rough categories of exposure outcome, outcomes measured directly are reported as continuous values (e.g., percentiles or percentage of time below/above certain levels), indicating how close they are to the recommended exposure limit. Precise measurements of exposure enables evaluation of small changes in the workload, a key aspect of improving working conditions or evaluating related proposals.

4.6 Epidemiological reference data

The comparison of the exposure profile of a manikin/manikin family during a simulated work task to the database of exposure profiles and health outcomes for various occupational groups, assumes that similar exposure will lead to a similar WMSD response. For the approach to successfully fulfil its purpose, it is imperative to have access to comprehensive reference data. Today's easy and inexpensive standardised methods for direct measurements, as well as systematic procedures for diagnosing health outcome, should allow this database to be extended and include additional occupational groups in the near future.

4.7 Group exposure profiles

The relationship between occupational exposure profiles and health outcomes are a common focus of epidemiological occupational health research (Bovenzi, 1994; Fallentin et al., 2001; Nordander et al., 1999). Exposure statistics from a sample of workers within the same occupation i.e., a group exposure profile – here demonstrated by a manikin family, describes the exposure within the sample. Hence, the manikin family may represent the within-group variation (e.g., due to anthropometric variation) which can be larger than the variations between different occupational groups (Fallentin et al., 2001).

4.8 Test case

The variance in level of exposure between the different members of the manikin family in the test case highlights the significance of within-group variation.

Since the exposure module in IMMA is still under development, for the transparency and simplicity, the risk analyses (which in the future will be automated) were performed in Excel.

However, the test task was very short, and in a real situation, a longer time period would allow more reliable comparison with the reference database. In the connection with final assembly of automobiles, work cycles of approximately one minute are common and may be repeated for two hours, followed by job rotation. In serial production with such short repetitive tasks, there is usually some recovery time, characterised by slower movements in neutral postures, included in the cycle time. Therefore, for a relevant assessment, the entire cycle time should be included, although the work moments may be finished in advance.

To simulate full-day exposure, all the workstations the workers rotate between would have to be included. Since the test case illustrates only the assessment of a minor part of the workday in a minor part of the plant, the presumptive WMSD prevalence is not indicative of the occupational health data of the factory. This prevalence might provide a valid estimate if this test task was repeated for entire workdays.

4.9 Limitations of the present approach

The version of IMMA utilised in this study enables computations of manikin postures and motions and the data export of joint angles and joint velocities. It also offers export of forces and moments needed to keep the biomechanical system in translational and rotational equilibrium. For a more complete ergonomic assessment, muscular load, an important risk factor associated with MSD (Thomsen et al., 2007), must be included. Numerous reports describe the handling of physical load and forceful gripping as a major risk factor for wrist-related disorders (Hagberg et al., 1992; Shiri et al., 2009; Silverstein et al., 1987), due e.g., to elevated pressure on the carpal tunnel (Armstrong and Chaffin, 1979). The ambition is that future versions of the presented approach to risk assessment will also include kinetics and muscular activity.

In addition, the approach includes neither psychosocial and environmental factors nor other factors such as vibration and temperature which may influence the development of WMSD. Instead, the primary focus is on assessing the risk of WMSD due to biomechanical load in a pre-production setting. As it should be possible to use the approach even in existing production, actions are planned to allow additional risk factors to be manually added.

Programming a manikin to move like a human is difficult. We have succeeded in that these movements look human on the video display, but do not yet know how closely the simulated group exposure profiles represent the real working population. One way of determining this would be to compare actual work exposure of a group performing a standardised task to the simulation, and such tests are now planned.

In practical terms, the approach described may be considered advanced, but there are several avenues for improvement. For example, to be accessible to non-experts (e.g., engineers and designers), it would be desirable for the assessment to provide some form of overall risk score, at least for each body part assessed. However, it will require considerable effort before such an epidemiologically based score can be presented.

The approach involves risk assessment for an entire workday, and how does one deal with the prevalence if a certain exposure occurs only during part of a workday? One common way is to analyse the task as if it were performed for a full day (i.e., summing up to full working time).

A more complex issue concerns how to establish an acceptable level of risk. Such an issue should be of concern for researchers, government, and companies alike and should lead to regulations regarding risk limits not attainable in practise.

4.10 Implications of the present findings

If work demands were designed to coincide with human capacities, WMSDs would not exist. In reality, risks are often difficult to identify in advance and, when they do arise, they are problematic and expensive to eliminate. Therefore, convenient and inexpensive tools for quantifying the risks for hazardous biomechanical exposure at an early stage in planning are highly desirable.

In industry, it is of interest to be able to predict the ergonomic effects of changes in the production system. The ambition of the present approach is to help with such early evaluation of design solutions from an ergonomic perspective, and where the quantitative measurements are used as arguments and guides for redesign of the work station/work place.

When the approach has become fully automated, it will become even more time-efficient in providing objective and quantitative information concerning both static and dynamic aspects of the workload. One advantage is that the approach is not limited to DHM tools but can also be used in field- and laboratory studies involving direct measurement of workload associated with complaints. This allows for evaluation of ergonomic interventions by using the same assessment strategy to monitor physical stress on existing workstations. The possibility to save exposure outcomes in a database will facilitate comparisons with earlier design solutions or suggestions aiding continuous improvement of the workplace as well as the development of products- and productions.

5 Conclusions

The present ergonomic DHM evaluation compares direct measurements to reference values for exposure and the prevalence of WMSDs. A number of relevant measures of exposure are included in order to objectively quantify and evaluate static and dynamic workload. The ability to obtain detailed information on movements and posture with computerised manikins is exploited. Since the assessment process is automated and built into a module of the DHM tool IMMA, it is time-efficient. An industrial test case, exemplifies usage of this approach. This approach should help both production engineers and designers to prioritise ergonomic needs and adjustments in connection with different design solutions. The approach should also be valuable for ergonomists, both in connection with preventive improvements of working conditions, as well as in the evaluation of, e.g., a workplace prior to intervention.

Currently, the approach does not incorporate exposure such as muscular load, for which high loads are associated with an increased risk for WMSDs. Therefore, to facilitate a more complete analysis, the IMMA manikin will be supplemented with kinetics for assessment of motion forces and moments. When that has been completed, the reference database needs to be extended to include other exposure variables.

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