ASSESSING ARM ELEVATION AT WORK WITH TECHNICAL SYSTEMS

PEROSH Joint Research Project

Recommendations for procedures to measure occupational physical activity and workload

PEROSH (Partnership for European Research in Occupational Safety and Health) is a Network of European Occupational Safety and Health research institutes.

PEROSH has developed several joint research projects. This report results from the project “Recommendations for procedures to measure occupational physical activity and workload” and was coordinated by NFA, IFA, INSST, CIOP-PIB, INRS, STAMI, FIOH, INAIL, HSE, AUVA, LU, KI and University of Gävle

Title:

"Assessing Arm Elevation at Work with Technical Assessment Systems."

DOI: 10.23775/20181201

Institutions collaborating on the report:

[1] Austrian Workers Compensation Board (AUVA), Vienna, Austria.
[2] Finnish Institute of Occupational Health (FIOH), Helsinki, Finland.
[3] University of Gävle, Gävle, Sweden.
[4] Health and Safety Executive (HSE), Buxton, United Kingdom.
[5] Institute for Occupational Safety and Health of the German Social Accident Insurance (IFA), Sankt Augustin, Germany.
[6] National Institute for Insurance against Accidents at Work (INAIL), Rome, Italy.
[7] French National Research and Safety Institute for the prevention of occupational accidents and diseases (INRS), Vandoeuvre les Nancy, France.
[8] National Institute of Safety, Health at Work (INSST), Madrid, Spain.
[9] Karolinska Institutet (KI), Stockholm, Sweden.
[10] Lund University (LU), Lund, Sweden.
[11] National Research Centre for the Working Environment (NFA), Copenhagen, Denmark.
[12] Netherlands Organisation for applied scientific research (TNO), The Hague, Netherlands.
[13] National Institute of Occupational Health (STAMI), Oslo, Norway.

Authors:
Britta Weber[5], Marjolein Douwes[12], Mikael Forsman[9], Reinier Könemann[12], Kai Heinrich[5], Henrik Enquist[10], Andrew Pinder[4], Anne Punakallio[2], Arja Uusitalo[2], Dirk Ditchen[5], Esa-Pekka Takala[2], Francesco Draicchio[6], Kevin Desbrosses[7], Michael Wichtl[1], Michaela Strebl[1], Morten Waersted[13], Nidhi Gupta[12], Norbert Lechner[1], Teresa Alvarez Bayona[8], Ulrike Hoehne-Hückstädt[5], Svend Erik Mathiassen[3], Andreas Holtermann[11], Kaj Bo Veiersted[13]

Disclaimer:
The information provided by this document is intended only to provide general assistance. This document neither contains nor replaces any statutory requirements under any European, international or national state legislation. Before relying on the material, users should carefully make their own assessment as to its accuracy, currency, completeness and relevance for their purpose. We also advise users to obtain appropriate professional advice relevant to their particular circumstances.

Table of contents

Assessing Arm Elevation at Work with Technical Systems

1 Introductory summary, aims and scope

Manual activity at work often involves exposure to arm elevation. Prolonged periods of arm elevation followed by insufficient recovery may be harmful to the musculoskeletal system, especially in the neck and shoulder region. Assumed health effects are dependent not only on the arm elevation *per se*, but also on other aspects of the biomechanical load, such as anatomical structures, elbow angle, use of muscle force, and handling of tools, including arm support. However, the present report focuses on arm elevation as a proxy measure of biomechanical load on the shoulder and does not consider the aforementioned additional aspects. In this report, we use the term *arm elevation* synonymously with the more precise term *upper arm elevation*.

The literature offers different definitions of arm elevation. The definition of *arm elevation* in the present report is: “the angle between the upper arm vector and the vertical line” (see Chapter 4). Most studies investigating the association between arm elevation at work and musculoskeletal health have concluded that arm elevation at work may increase the risk of disorders. However, some studies show inconsistent results. This may be explained by arm elevation assessment having been performed by various methods, primarily self-reports. Self-reports have a rather low accuracy, whereas a technical method of assessing the exposure yields more accurate estimates and even offers the possibility of assessing movements and the time distribution of the exposure. In order to identify load bottlenecks and investigate the link to musculoskeletal health, it is crucial for arm elevation at work to be quantified accurately. Prospective studies employing technical measurements are needed in order to investigate the extent to which occupational arm elevation, including its temporal characteristics, can be assumed a causal risk factor for health impairments. This is an essential prerequisite for deriving epidemiologically based preventive recommendations.

A range of sensor technologies and measuring systems are available for assessment of arm elevation at work. This results in a need for practical guidance for practitioners and researchers in selecting the appropriate instrumentation and measurement strategy. Guidance can also facilitate harmonized application and interpretation of the various technical methods for both practitioners and researchers.

The main aim of this report is to present practical guidance on technical systems for assessing arm elevation. The focus is on assessment of arm elevation during occupational work, but the guidance may also be used for general purposes. The report provides a definition and operationalization of *arm elevation* and an overview of generally available assessment methods, paying special attention to technical systems. In addition, assistance is provided in selecting and using an appropriate method for a specific purpose, including selection of (a) device(s), deciding on a sampling strategy, and interpreting the measurement results. Finally, the report highlights the need for technical systems to be used to assess arm elevation and for devices to be developed (further) that are easy to use for both data collection and analysis.

2 Arm elevation at work – health effects

2.1 Potential health effects

The main health effects in jobs involving excessive arm elevation are pain conditions and reduced function in the musculoskeletal system. These are mostly non-specific and described as "symptoms", "complaints", "problems", "aches" or "troubles", but may also be described more specifically as illnesses or diseases. Specific disorders associated with excessive biomechanical loading of the shoulder are mostly related to:
1) tendon disorders mainly in the complex of the rotator cuff, which may result in a chronic pathologic defect of the tendons, and
2) disorders of the large muscles stabilizing the scapula (the trapezius being the most common location of discomfort). These diagnoses include non-specific neck pain and tension neck syndrome. Epidemiological research often does not distinguish between these outcomes.

The mechanisms for the pathophysiology, relating arm elevation at work to impaired musculoskeletal health, have been widely discussed. Arm elevation is a proxy measure of biomechanical load on the shoulder, and excessively high loads can cause adverse effects in the tissues. A consensus does not exist, however. Muscular fatigue [1, 2], prolonged muscle activation [3, 4] cumulative trauma disorder [2], inflammatory processes [5], reduced microcirculation [4, 6] and mechanical static or repetitive pressure on the tendons [7] are all suggested as possible and plausible mechanisms.

Cardiovascular symptoms (e.g. hypertension) have also been associated with arm elevation [8, 9]. A possible causal effect of work with the arms elevated, especially static muscle contractions, on cardiovascular symptoms is at this stage dubious and not included in this report.

2.2 Musculoskeletal health effects

Many studies have investigated the relationship between arm elevation at work and musculoskeletal disorders (MSDs). Several reviews conclude that exposure to arm elevation at work constitutes an important risk factor for shoulder pain [10, 11] and specific shoulder disorders [12, 13], even when only studies with prospective design are considered [14, 15]. A review published in 2000 found inconclusive evidence of an association between arm elevation at work and neck pain [16]; another review, published in 2017, found limited evidence of a harmful association between arm elevation at work and neck pain [17].

Danish researchers have at their disposal a database of approximately 40,000 individuals from nine studies in which experts assessed the mechanical (physical) exposure for 172 groups of jobs [18]. They found that the risk of surgery for subacromial impingement syndrome was increased in jobs for which the experts had estimated arm elevation to be >90°, even with a duration of less than 1 hour/day.

Researchers in the USA video-taped workers at an automobile assembly plant and found an increased risk of shoulder disorders when the elbow was above shoulder level for more than 10% of the work cycle time [19].

An analysis of data pooled from a series of cross-sectional studies (comprising 33 occupational groups in total) found harmful exposure-response relationships between objective measures (determined by inclinometry) of right arm elevation and diagnosed neck/shoulder disorders [20]. A study evaluating the relationship between objectively measured periods with elbows above shoulder level and shoulder disorders found an exposure-response relationship between current arm elevation and shoulder disorders [21]. A prolonged objectively measured arm elevation above 60° and 90° for periods of >5 s in duration has been associated with later shoulder pain in young women [22]. A study of construction and healthcare workers found associations between arm elevation at work assessed by inclinometry and shoulder pain in the unexpected direction (more pain for the less exposed workers). The associations were evident both at baseline and after 6 months, but were not statistically significant [23]. No association was found between exposure to static periods with elevated arms (> 4 s) and neck/shoulder pain.

Arm elevation at work has been associated with low back pain in some longitudinal studies [24, 25], but not in other studies [26, 27]. These studies were all based on self-reports of exposure.

Overall, literature findings point to associations between arm elevation at work and musculoskeletal health effects, but findings are not consistent. This emphasizes the need for more research in this field, particularly involving technical measurements of arm elevation at work and prospective follow-up on MSDs.

Arm elevation at work has been associated with other outcomes related to MSDs. An intervention on the work environment, including mechanical exposures, showed that reduced self-reported arm elevation at work was associated with reduced sickness absence due to MSDs in general [28]. Self-reported "arms above shoulder height" in the general working population for more than 25% compared to below 12% of working time corresponds to an increase in long-term sickness absence of approximately 50% [29]. In a Norwegian cohort study, working with the hands above shoulder height was found to increase the risk of work disability in the general working population [30].

2.3 Key messages – health effects

The pathophysiological mechanisms that link arm elevation at work to adverse health outcomes are unknown, but hypotheses exist that make a causal relationship plausible.

According to the literature, arm elevation at work is generally considered to be a risk factor for shoulder disorders, but with less certainty in relation to neck pain, and even less for low back pain.

Many studies using self-reported arm elevation assessment have found a harmful association with musculoskeletal health. However, the results across studies using different assessment methods are heterogeneous, requiring prospective studies using technical measurements of arm elevation.

3 Arm elevation at work – prevalence of exposure

3.1 Prevalence in the general population

Questionnaires or interviews are often applied to analyse exposure in national surveys or similar studies. The Scandinavian countries have a similar wording of the question: "Do you work with hands at or above shoulder level? If yes: for how much time daily?". Thirteen % of the workforce in Norway [31], 17% in Sweden [32] and just above 20% in Denmark [33] report being subjected to this exposure for more than 25% of the working day. Comparable figures are available from a questionnaire-based survey of the French working population. Thirteen % of the respondents stated that they "worked with arms above the shoulder" for at least 2 hours per day [34]. In a Finnish survey in 2012, 9% of respondents answered that they work with one or both hands above shoulder level for more than 1-2 hours daily [35]. We have found neither national surveys from other countries that pose a similar question, nor questions concerning more precise measures of amplitude and duration [36].

3.2 Prevalence in occupations particularly exposed to arm elevation at work

Examples of extensive arm elevation at work can be found in the construction industry (electricians, painters, plasterers and drywall builders), in the automotive industry (special assembling processes), in general maintenance work, and among dentists and hairdressers. In the Norwegian survey data, 62% of the carpenters reported working 25% or more of the working day with hands at or above shoulder level. Corresponding figures were 52% for hairdressers, 42% for electricians, 31% for mechanics and 23% for workers in the retail sector [31].

The fraction of the working day during which work was performed with the arms elevated has been measured in many occupations by inclinometers/accelerometers [20, 37]. Hairdressers work with the right arm elevated above 60° for 7% of the working day [38]. A study employing shorter measurement times showed that hairdressers work 48% of the time with arms elevated above 30°, 13% of the time with arms elevated above 60° and 3% of the time with arms elevated above 90° [39]. Work with the elbow above shoulder height (>90°, "severe arm elevation") has been used as an indicator in many studies. Machinists work with this severe arm elevation for 2%, car mechanics for 5%, painters for 9% [21] and electricians for 9% of the working day [40]. Automobile assembly work has been evaluated by video, revealing severe arm elevation among the workers for approximately 8% of the work cycle time [19].

The high prevalence of both self-reported and objectively assessed time with arm elevation at work, and its possible relation to MSDs, underlines the need for more knowledge of valid dose-response relationships between work with elevated arm and MSDs. However, accurate and reliable exposure data are necessary in order for valid dose-response relationships to be derived and valid tools obtained for designing and evaluating interventions in working life.

3.3 Key messages – prevalence of exposure

In several western European countries, 9 to 20% of the workforce report elevated arms at work (assessed as working with hands/arms at or above shoulder height) for more than 25% of the working time. Workers in certain occupations report much higher levels.

The longest durations of arm elevation have been determined via measurements in workers such as painters and electricians, who spend approximately 10% of their working time with the elbow above the shoulder.

4 Arm elevation at work – definition and rationale of measurement strategies

Different definitions of work with arm elevation are found in the literature. Examples are: "work above shoulder height" (e.g. [24]), "hands above shoulder height" [31, 41] and "overhead work"[42, 43]. These are imprecise descriptions or definitions of the amplitude of arm elevation and can easily be misunderstood by both practitioners and researchers, thus complicating comparisons between studies. For example, the location of the upper arm cannot be deduced from the hand position. "Hands above shoulder height" can be reached with the upper arms resting on the upper body (upper arms near the vertical line) or with elevated upper arms (upper arms near the vertical line). Moreover, the frequency and time patterns of arm elevation and the movement velocity are important, as well as the total time with "elevated" arms. This chapter therefore aims to define arm elevation at work and to describe how it can be characterized.

4.1 How to define arm elevation

The shoulder is a very complex joint system, and a range of biomechanical approaches are found in the literature describing its movements. For example, the International Society of Biomechanics (ISB) recommends a very elaborate model [44]. Other studies use more simple descriptions of the shoulder-arm system [45-47]. Anatomically, arm elevation represents a combination of upper arm movement in the coronal plane (abduction-adduction) and the sagittal plane (flexion/extension). Rab et al. (2002) simply calculated the angle between the humerus (upper arm) and the trunk to determine the upper extremity kinematics [46].

In order to meet the particular requirements for measurements to be as simple as possible, we propose the following simplified definition: "the angle between the upper arm vector and the vertical line" (see Figure 3A). The "upper arm vector" is defined as the line from the shoulder joint centre (glenohumeral rotation centre) to the elbow joint centre (midpoint of lateral and medial epicondyle). The vertical line is defined as the gravitational vector pointing downwards.

For measurement of the arm elevation angle, determining a reference posture (0°) with arms hanging freely parallel to the vertical line is recommended (see Figure 3C; [48]). A weight in the hand can facilitate more precise attainment of the vertical line. The reference position can be determined with the subject both sitting and standing. The arm elevation is, by definition, 90° when the arm vector is parallel to the transversal plane.

This simplified definition of a "global" arm elevation angle is based on the assumption of an upright trunk posture. Should inclined trunk postures occur, the "local" angle between the upper arm and the trunk may also be relevant. The local angle between upper arm and trunk may be large even when the global arm elevation angle is small, e.g. during road paving work.

4.2 Other relevant aspects with respect to shoulder load

The proposed definition of arm elevation is, in general, indicative of what is probably the most important aspect of shoulder load, i.e. the biomechanical moment resulting from the weight of the arm. The definition takes into account only the spatial position of the upper arm relative to the vertical line, and not the angle between upper arm and trunk. Depending on the direction of movement, the passive and active structures of the shoulder joint are loaded differently. In some cases, it may therefore be important to distinguish between arm elevation in the coronal plane (abduction and adduction) and in the sagittal plane (flexion and extension). In these cases, a more complex measurement system is needed, as will be explained in Chapter 6.

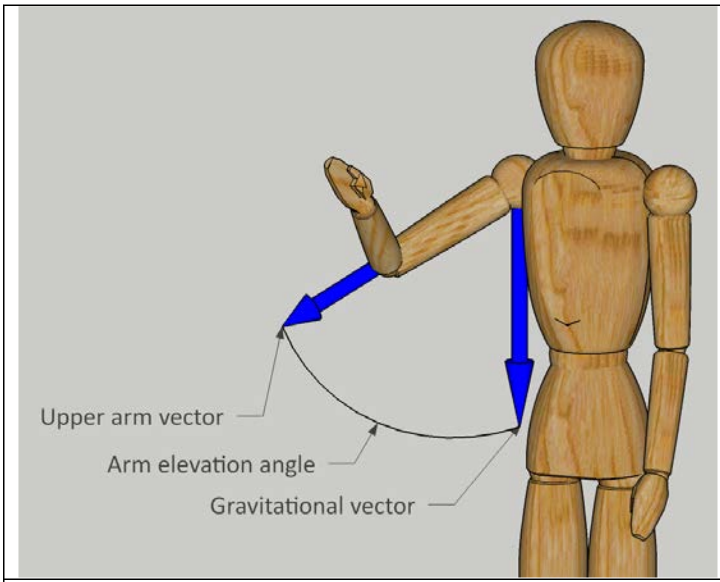

Figure 3A. Arm elevation angle: the angle between the upper arm vector and the vertical line pointing downwards

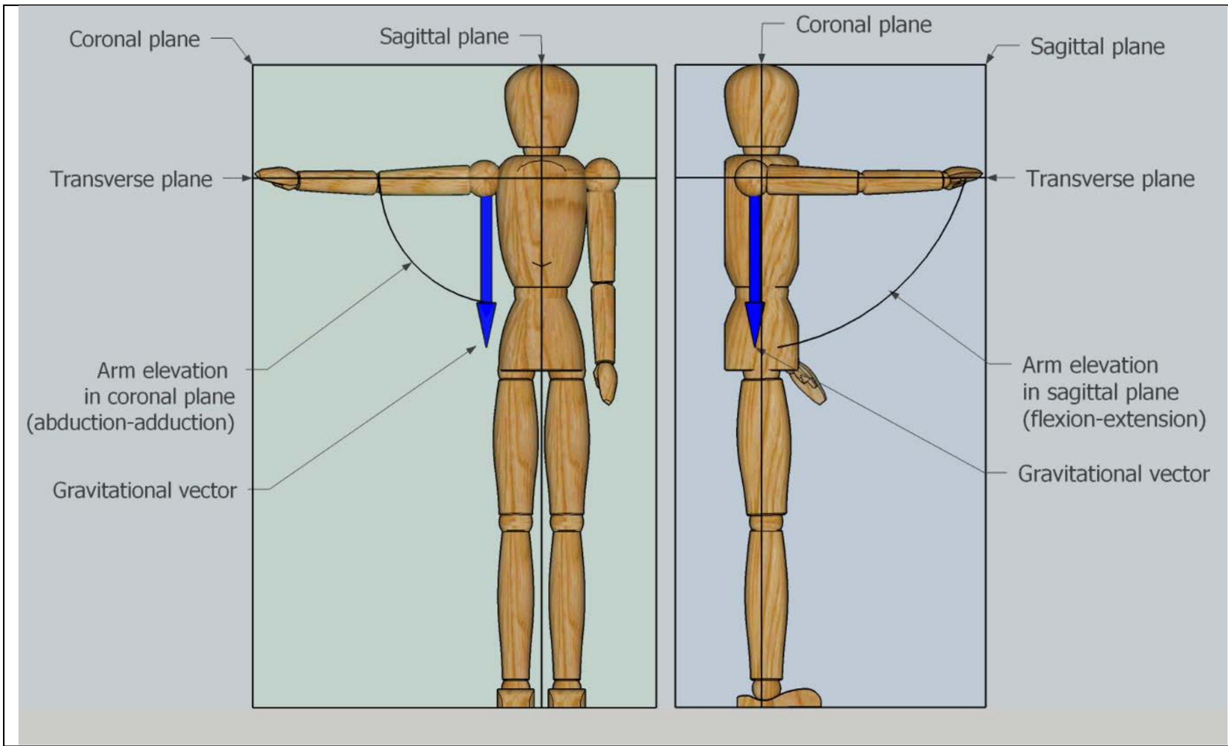

Figure 3B. Arm elevation in the coronal plane (abduction-adduction) and in the sagittal plane (flexion-extension)

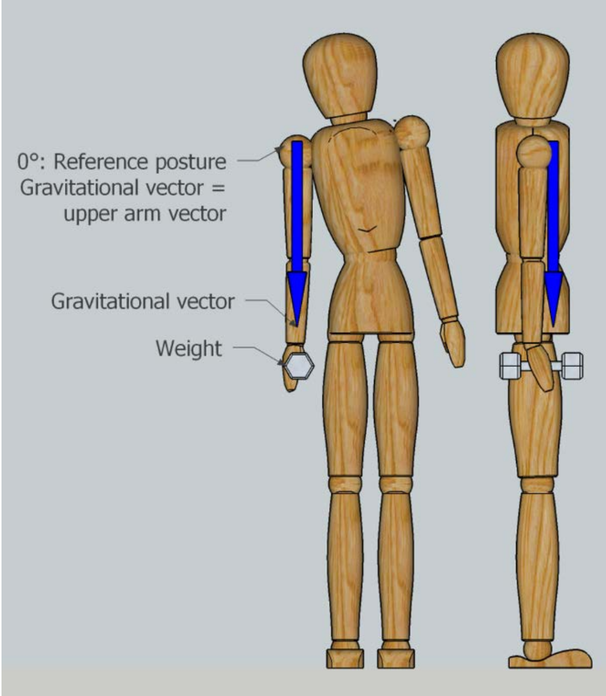

Figure 3C. Reference postures for measuring the arm elevation angle: upper arm parallel to the vertical line (0°)

Table 4.1. Explanation of relevant terms with respect to arm elevation measurement

Terms	Definition used in this document
Upper arm (humerus) vector	*Imaginary line from the shoulder (glenohumeral rotation centre) to the elbow (midpoint of lateral and medial epicondyle)*
Arm elevation angle	*Angle between the upper arm vector and the vertical line (between 0 and 180°)*
Vertical line	*Gravitational vector pointing downwards*
Reference posture of arm	*Arms hanging down, parallel to the vertical line (0°)*
Sagittal plane	*Anatomical Y-Z plane dividing the body into a left and a right part; perpendicular to the coronal and transverse plane*
Coronal plane	*Anatomical X-Y plane dividing the body into a back and a front part; perpendicular to the sagittal and transverse plane*
Transverse plane	*Anatomical X-Z plane dividing the body into an upper and a lower part; perpendicular to the sagittal and coronal plane*
Shoulder abduction/ adduction	*Motion of the arm in the coronal plane away from the midline of the body*
Shoulder flexion/extension	*Motion of the arm in the sagittal plane towards the midline of the body*
Frequency	*Incidence of a specific event per unit time, e.g. arm movement above a certain arm elevation angle*
Angular velocity	*Absolute angular changes per unit time*

4.3 How to characterize arm elevation

During studies of the physical workload related to arm elevation, several exposure dimensions of a continuous time series of arm elevation may be relevant, i.e. the amplitude, duration, frequency or angular velocity and time pattern of arm elevation. The following paragraphs describe these major exposure dimensions. A more comprehensive description of relevant variables that can be derived from a time-line of arm elevation can be found in Appendix A.

In addition, the biomechanical shoulder load and therefore the muscle load depends on further factors such as external force exertion and arm support. These factors are not considered below; they are beyond the scope of the report.

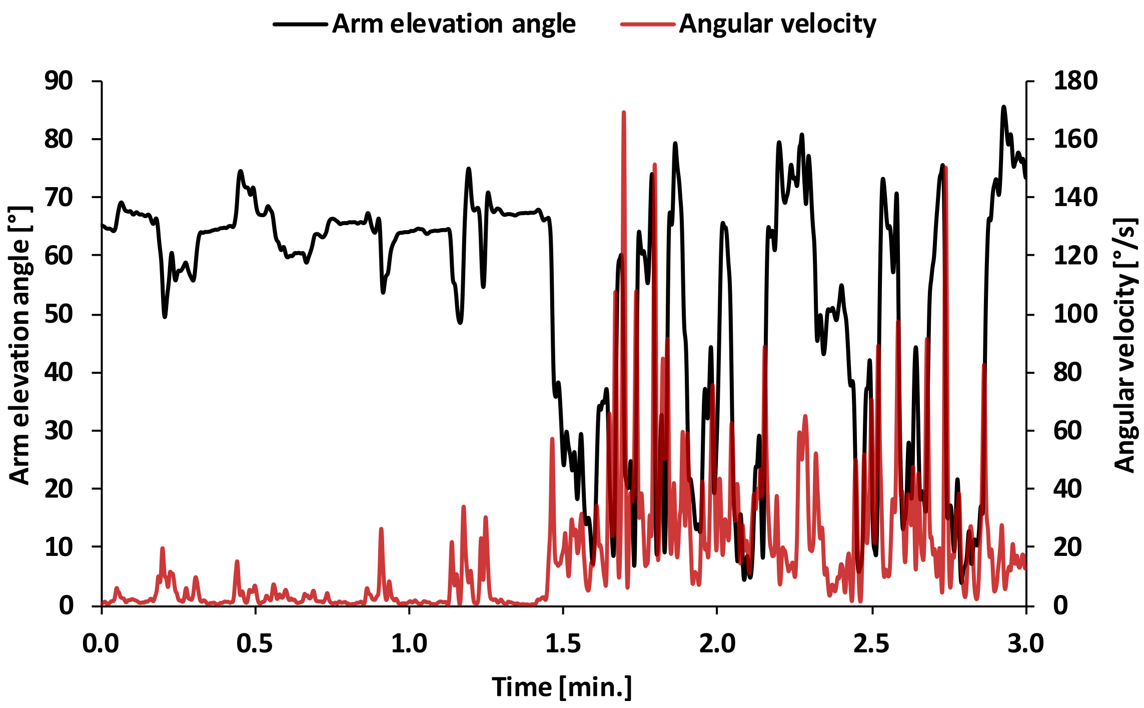

Figure 3D. Example of a time-line of arm elevation angle (black) and angular velocity (red)

Amplitude of arm elevation

The amplitude of arm elevation (intensity of the exposure) can be represented by a number of summary measures. By our definition, the angle describing upper arm position in relation to the vertical line (i.e. the arm elevation angle) is of major interest.

Duration

The most common duration metric is the total duration of increased arm elevation during the working day; it expresses the cumulative aspect of the exposure. A single action with a large arm elevation is likely to be of no hazard, even if the situational assessment indicates an “unacceptable” arm position according to international standards. To obtain more insight into exposure limits related to MSD, future research needs to capture the daily duration of work with increased arm elevation, as well as the total number of days when these exposures are present. Additionally, the duration of single events of arm elevation is of importance, since it indicates the extent of variation in postural load.

Frequency or angular velocity

Beside the arm elevation amplitude, the frequency of arm elevation events is an important dimension characterizing the exposure. A typical question may be "How many arm elevations per minute/hour/day have been performed?". High frequency may indicate repetitive movements, which are known risk factors for several disorders of the upper extremities and therefore a crucial measure to be captured. Alternatively, the angular velocity of arm elevation movement may be used to combine the two variables of arm elevation amplitude and frequency. An advantage of this alternative measure is that it includes the full angular movement and is independent of a certain cut-off angle.

Time patterns: exposure and recovery

Another important aspect in the context of MSD risk associated with arm elevation is the time distribution of periods at different exposure amplitudes: does the time-line of exposure allow sufficient *time for recovery* from periods with high elevation ("effective breaks")?

4.4 Key messages – definition

Different definitions of work with arm elevation are found in the literature. In this report, arm elevation is defined as: "the angle between the upper arm vector and the vertical line".

The '0°-position' of the arm (arms parallel to the vertical line) is used as a reference posture for the measurement of arm elevation.

During evaluation of exposure to arm elevation, the amplitude (angle) and time characteristics, i.e. duration, frequency, angular velocity and time patterns of arm elevation, should be considered.

5 Arm elevation at work – how to assess

Arm elevation at work has been assessed by various means, including self-reports, observations and technical instruments. This chapter briefly presents these methods and their strengths and limitations.

5.1 Self-report measures

In epidemiological studies, exposure assessment of arm elevation during work is usually based on self-reports [49, 50]. The use of self-administered questionnaires for exposure assessment offers a number of advantages such as low cost, simple and quick handling and thus applicability for large samples. In addition, they enable exposures to be examined retrospectively. Nevertheless, the information obtained must be analysed with care, as the results may be of poor precision and highly biased, leading to a low validity of the assessment [51-53].

Questionnaires and interviews often survey the total duration of hands above shoulder height, overhead work or arm elevation above a certain angle (e.g. ≥ 60°) throughout the working day with answers assigned to different time categories (e.g. ≥ 2 hours). Whether the self-reports provide the relevant information for arm raising according to our definition therefore depends on the response categories (see Chapter 4). Depending on the questions, self-reports can roughly indicate the total duration of elevated arms within a certain angle range. They cannot provide differentiated information on aspects such as the amplitude, the duration of individual events and the frequency/angular velocity or time pattern of the arm elevation.

Depending on the aim of the investigation, the accuracy of self-reports on arm elevation during work may not be sufficient. In this case, the user must choose more precise and valid measurement methods. Even when employing other methods to record arm elevation, questionnaires can still provide valuable additional information, such as subjective measures of physical strain or whether the arms were supported during certain tasks.

5.2 Observational methods

In comparison to self-reports, observational methods may, in many cases, provide more valid information on arm elevation at work.

Different types of screening tool are available to support the observations, their suitability depending on both the experience of the user and the aim of the investigation. Generally, such relevant observational methods are designed for risk assessment of physically demanding work. They do not therefore focus exclusively on elevated arms, but evaluate the postural loading on the upper limb or even on the whole body as at least one of several possible risk factors.

Typical examples of the overall observational postural approach are methods such as OWAS (Ovako working posture assessment system [54]), QEC (Quick exposure check [55]) and REBA (Rapid entire body assessment [56]). A more detailed observational approach regarding the load on the upper extremities in repetitive tasks is represented by methods such as RULA (Rapid upper limb assessment [57]), the OCRA index and OCRA checklist (Occupational repetitive actions, [58, 59]), LUBA (technique for postural loading on the upper body assessment [60]) or HARM (Hand Arm Risk Assessment Method [61, 62]. Further methods and the respective advantages and drawbacks of a large range of observational methods can be found in Takala et al. [63].

In principle, all characteristics according to our definition (see Chapter 4) can be estimated by observational methods, and some observational studies do, indeed, attempt to determine summary metrics on arm elevation during occupational work, typically by post-hoc observation of video recordings [64-66]. The quality of the collected data depends highly on whether the observed work is clearly visible, and on the observer's motivation, alertness, education, and experience. The variability both between and within observers in estimates of arm elevation may be substantial [64, 65, 67]. Particularly, the assessment of highly dynamic or complex activities and activities with frequent changes of location may cause misjudgment, even with video recordings of good quality. In contrast to self-reports, which can also be used retrospectively, observational tools are usually limited to the assessment of currently existing workplaces. Moreover, post-hoc observation of arm elevation can be time-consuming, depending on the observation procedure used [65]. However, observations have the advantage that information on the context, e.g. tasks and activities, breaks and factors such as arm support can be included in data collection. This information may be crucial for a good interpretation of the arm elevation data.

5.3 Technical measurements

Technical measurements offer the opportunity to collect accurate data on ongoing processes at the workplace with high validity and reliability. It has long been recognized that dynamic work is best quantified by means of technical measurements [68, 69]. Arm elevation can be measured by different motion capturing techniques.

One way to measure postures and movements very accurately is through optical motion capturing techniques. The principle of optical motion capturing is employed in systems that yield highly accurate position coordinates of reflective markers placed in specific locations on the body. The systems use a set-up of multiple synchronized cameras (or electromagnetic equivalents where electromagnetic markers are employed) to capture each marker's location. However, since the space covered by the cameras is limited, these motion capturing systems are less feasible for data collection in real-life work environments. Nevertheless, they are useful in validation of new field-applicable systems.

This report will focus on mobile systems that are suitable for field studies. These systems are able to detect the position and/or movement of body parts from one or more body-worn motion sensors, such as accelerometers, gyroscopes, potentiometers and combinations of these sensors. Placed in defined positions on body segments, they provide information on spatial orientation. Body-worn sensors enable all characteristics of arm elevation (see Chapter 4.3) to be assessed with high accuracy.

A general opinion of technical measurements has been that they are time-consuming and require expensive equipment and considerable technical competence in use [70, 71]. They are indeed usually more time-consuming and thus more expensive than self-reports [72]. However, compared to observations, direct measurements are less time-consuming in the data processing phase, at least in cases where processing of the direct measurements is automated to a large extent [66]. Thus, in a study comparing observations and inclinometer measurements with respect to both data quality and costs, Trask et al. concluded: "Since observations were biased, inclinometers consistently outperformed observations when both bias and precision were included in statistical performance" [73].

Ongoing technical development has led to miniaturization, simplified application, widespread availability, and greatly diminished costs of the equipment [74]. This has increased the feasibility of objectively assessing arm elevation on larger populations during work in real-life settings with minimal effect on working techniques, performance and productivity. In addition to the cost of the equipment, the extent of automation in data collection and data processing determines the costs for the use of motion sensors, and considerable developments have also been made in this respect.

Since many aspects of work cannot be assessed by technical measurements, it can be meaningful or even necessary to use observational methods and/or self-reports in addition to technical measurements. For example, in order to interpret the results of the measurements, it can be necessary to know which activities were performed, when breaks occurred, when the arms were supported, etc. When mobile motion capturing technology is used, it is important to distinguish between applications with or without additional observation. The degree of differentiation and the explanatory power of measurements without observation are lower than in measurements with observation.

Considering the general advantages of technical measurements in their accuracy and reliability, and the technical progress in developing easy-to-use instruments, we recommend that arm elevation during work be assessed with the use of motion sensors rather than solely by observational methods or self-reports.

Many different measurement techniques exist – covering both true expert methods and “easy-to-use devices” – and they are not equally suited for all purposes and target groups. However, no standard procedures and recommendations are currently available for assessing arm elevation at work.

5.4 Key messages – how to assess

Self-reports yield inaccurate and biased information on arm elevation at work. However, they can deliver valuable contextual information when used in conjunction with other methods.

More detailed information can be obtained by observational methods; the quality of this data depends however on observers’ competencies, and such methods are less feasible for highly dynamic or mobile workplaces. In addition, observations are often time-consuming, less precise and less reliable due to observer variability.

Technical measurements supply accurate and precise data. Due to the ongoing technical developments, they are becoming even more feasible, and less expensive. Observational methods used as a supplement to technical measurements may assist in providing contextual information facilitating interpretation.

Technical measurements are recommended due to their accuracy, their objective nature and their widespread application spectrum.

6 Arm elevation at work – available technical systems

6.1 What principal sensor technologies are used to quantify arm elevation?

Several sensor technologies have been employed for field measurements of arm elevation at work, as shown in Table 6.1.

Table 6.1. Sensor technologies that have been proposed to quantify elevated arms in a biomechanical workload context

Principle	Pros	Cons	References
Mercury switches in 15° intervals with external loggers	Robust Pioneering Errors of switches lower than 3°	Low resolution Not possible to measure velocity	[21, 75-77]
Potentiometers with external loggers	Robust Pioneering	Low accuracy Uncomfortable equipment and cables	[78, 79]
Accelerometers with external loggers	Accurate in static postures, synchronized channels	Inherent errors at high angular velocity, cables	[51, 80]
Accelerometers with on-device loggers	Accurate in static postures, facilitate multi-work day collections	Inherent errors at high angular velocity	[74, 81, 82]
Accelerometers + gyroscopes + magnetometers (IMUs) with on-device loggers	Highly accurate	Consume more battery power than devices employing accelerometers alone	[83-85]

Most of the sensors listed measure the absolute orientation in relation to the gravitational axis. Only the potentiometer measures angles in a body-fixed reference system, by registering the change in resistance undergone by the potentiometer spindle when the angle between the two lever arms of the potentiometer changes. In an early gravity-based method, seven mercury switches were used to register time in 15° intervals from 0° to 90° and above 90° [75]. Tri-axial accelerometers have been used in many scientific studies involving technical measurements of arm elevation. In the majority of these studies, the systems have included a separate data logger. The use of accelerometer devices with built-in data-loggers is now common [81, 86]. A tri-axial accelerometer measures the forces of gravity and acceleration acting on the sensor, in three dimensions. When the total amplitude, in the three axes, is close to 1 G (G is approximately equal to 9.8 m/s^2, or 9.8 N/kg), the angle from the vertical line may be derived with a high accuracy [51]. However, during rapid movements (inducing acceleration and high total amplitude), a significant error arises in the angle estimation [84, 87, 88]. Inertial measurement units (IMUs) employing integrated three-axial gyroscopes, accelerometers and magnetometers that are small and useful for arm elevation measurements have now been produced. Different algorithms exist for analysing the data from the IMUs data in order to obtain the direction of the sensor. In an industrial environment, the earth's magnetic field is often disturbed by iron structures. According to the present definition (see Chapter 4.1), the arm elevation is the direction of the arm in relation to the vertical line (the zero degree elevation). There is therefore no need to use the information from the magnetometer of the IMU, as elevation angles may be obtained from the IMU's accelerometer and gyroscope data.

Figure 6.1 shows arm elevation angles obtained from one accelerometer, a combination of accelerometer and gyroscope, and a highly accurate optical system (see Chapter 5.3) serving as a reference, during three different arm movement paces. The curves show by way of example that the faster the movements are, the higher the error will be in the accelerometer-based inclination estimates. Accelerometers are thus appropriate for inclination estimates if static postures or slow movements are expected or if the inclination need not be determined with high precision during rapid movements.

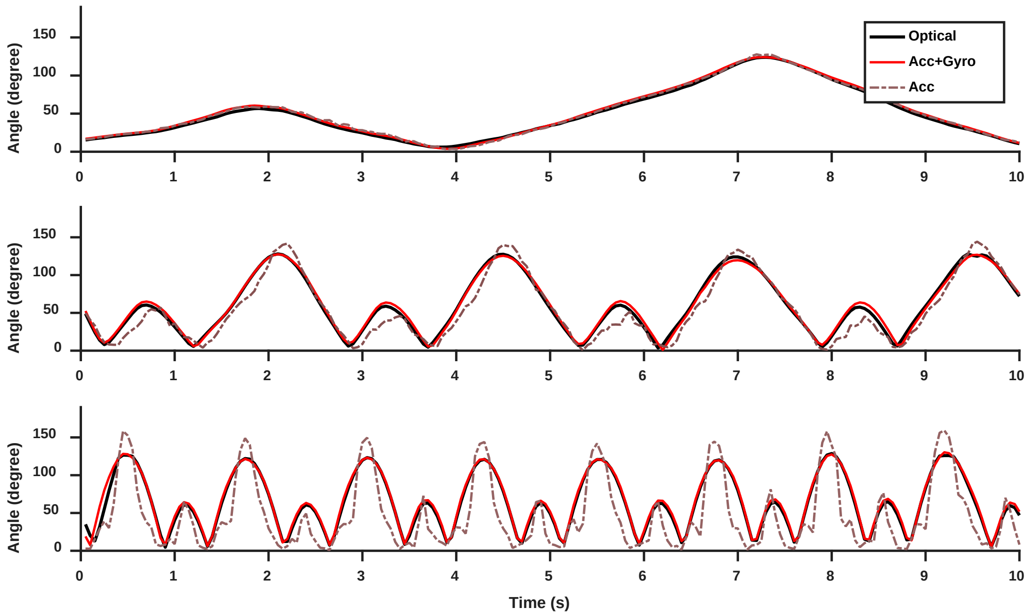

Figure 6.1. Estimated arm elevation angles with three techniques, during arm movements of three different paces (data from [84])

Note: The subject performed arm swings in the sagittal plane, in three different paces: 6 swings per minute, 24 swings per minute and 48 swings per minute. In the 10 seconds shown, the median angular velocity was 32, 152, and 274 °/s respectively.

6.2 What measuring systems are available?

Several systems are available employing the sensor technologies described above (see Table 6.1). These are mainly systems employing accelerometers or IMUs, ranging over different levels of complexity: single or multiple accelerometer systems, and single or multiple IMU systems. Systems that combine potentiometers and IMUs have also been developed [89-91]. The most commonly used systems, typically systems that consist of either accelerometers or IMUs, are discussed below. The current systems generally include tri-axial sensors.

The IMU systems deliver the highest accuracy. This complicates comparisons of velocity measurements from accelerometer systems with those from IMU systems. As may be seen in Figure 6.1, movements also induce errors in angle estimation.

6.2.1 Accelerometer systems

Of the principles described above, that most commonly used in field research projects is the accelerometer-based inclinometer [39, 51, 86], which during the last decade has become available in practical inexpensive devices.

The first generations of accelerometer systems, including cable-connected accelerometers and data loggers, became available commercially in the 1990s. These systems were initially expensive (around 4,000 Euros) and their application required special skills.

Several accelerometer-based devices with built-in loggers are now commercially available [81, 82, 84, 86]. Advantages of this new generation of accelerometers include their price (around 100-300 Euros) and that they do not need to be connected to a separate data logger. Further, their memory and battery capacity permit measurements over several consecutive working days (up to one month of continuous data sampling). Validated software for processing the data has been developed (such as Acti4; [81]), but data processing and analysis is still somewhat complicated and thus less suitable for practitioners than for research purposes.

However, less complicated methods for measuring arm postures and movements have been proposed. Dahlqvist et al (2017) developed and validated a protocol employing user-friendly software for an accelerometer with device-integrated memory [74]. Following data sampling, the device is connected to a computer and the output in the form of elevation angles and movement velocities is imported in the form of figures and tables into an Excel sheet. This method was shown to be valid against an accelerometer system validated previously [51]. Another, similar analysis application has been implemented in the form of an Excel macro. In this case, the accelerometer with integrated memory is attached to the upper arm. Following measurement, parameters of angles are computed and shown in Excel [92].

6.2.2 IMU systems

Owing to their usefulness in other fields, primarily in the gaming industry and in sports training, the technical base IMU component is now manufactured in small and inexpensive form (the component itself costs around 30 Euros). Inexpensive IMU devices with built-in loggers are also available, as are IMUs forming parts of much more expensive multi-sensor systems with a wireless connection to a master sensor or to a separate logger and display system, which also include advanced software.

In this category, a method for shorter measurements of arm elevation has been developed as an application for iPhone/iPod (ErgoArmMeter). Directly after a measurement, it displays statistical parameters of angles and angular velocities, together with recommended action limits [84]. As this method uses the built-in gyroscope and accelerometer of the iPhone, it is significantly more accurate during fast arm movements than systems that are based on accelerometers alone (see Figure 6.1).

To our knowledge, no such non-complex software exists as yet for the inexpensive IMUs with built-in loggers; such methods/software may however soon become available. They would then be a very attractive tool since, as shown in Figure 6.1, angles obtained by analyses of gyroscope and accelerometer data are highly accurate.

Several multi-sensor IMU systems are available; these are highly accurate, especially for the elevated arm angle, which as mentioned above may be obtained without use of the magnetometer signal. The magnetometer also enables the arms’ direction in the horizontal plane to be obtained (by use of a reference IMU fixed to the trunk). Commercially available multi-sensor IMU systems have been validated against lab-based optical motion capturing, and have shown reasonably high accuracy for arm elevation angles [93, 94]. Errors may be large in environments exhibiting disturbed magnetic fields. Non-commercial multi-sensor IMU systems have also been developed that address this issue by way of special algorithms that reduce orientation error by combining additional heading information and bidirectional computation of the IMU data [95].

The battery life of IMU systems is in general shorter than that of accelerometer systems. IMUs currently permit measurement over one working day, but as yet not much longer. Multi-sensor IMU systems continue to be expensive and complicated to use, and their data handling and analysis program are developed for experts.

6.3 How to analyze the measurement data

Measurement of arm elevation at work may be of interest in several different contexts, including assessment and surveillance of assumed hazardous exposures, and evaluation of whether interventions with a possible effect on arm elevation have been effective. Thus, in most cases, assessments are intended to reflect postures, movements or movement patterns assumed to be associated with (preferentially adverse) health effects, or with precursors of health problems such as fatigue. The technical systems described in this report produce an essentially “complete” time-line of arm elevation, and informative variables need to be extracted from these large volumes of data. However, no consensus exists in the scientific community on which specific arm elevation variables should be selected for the evaluation of expected consequences for health; exposure-outcome associations between arm elevation (as described by different variables) and expressions of disorders and fatigue have been described in various ways. Hypotheses have been formulated concerning the exposures that would be relevant for work tasks involving arm elevation; examples are the occurrence and timing of periods with “extreme” arm elevation, the occurrence and frequency of periods with neutral postures (representing “rest” or “recovery”), and movement velocity. Appendix A offers a list of variables that take up these aspects in terms of different metrics, and we propose that future studies should use and report on an extensive selection of these variables, as in examples elsewhere [38, 86]. Details concerning exposure patterns beyond those offered by the variables in Appendix A may obviously be of relevance in some cases, as provided for instance by a full Exposure Variation Analysis [96]. In addition, certain basic exposure properties that may eventually be seen to be important in the context of health are not addressed by the variables in Appendix A; examples are aspects of variation such as the extent to which specific exposure patterns occur repeatedly (“similarity”), and the temporal order of periods exhibiting different exposures [96].

6.4 How to choose the appropriate system

For selection of a suitable system, it is important to consider the aim of the study and several criteria related to this aim. The aim could be to perform a risk assessment on a group or individual level, to evaluate interventions or to monitor individual exposure with the purpose of providing feedback to the employee (see Chapter 9 for examples).
Several criteria should be considered in relation to the aim of the study and practical restrictions. Examples are:

- the required output accuracy, especially with respect to arm elevation velocity,
- the required duration of data collection (battery life requirement),

- the number of subjects required (see Chapter 7 for a comprehensive description of the measurement strategy) in relation to the available project budget, and
- the need for access to raw data and preprocessing processes.

The characteristics of the different systems available are presented in Table 6.4 and are explained below. The scenarios in Chapter 9 illustrate possible use cases of different systems depending on these characteristics.

Output accuracy
The required accuracy of output parameters depends on the aim of the project and the characteristics of the task. For example, precise analyses of activities in which high movement speeds are expected require outcome data with high resolution and high output accuracy. In this case, an IMU is recommended. For investigation of static postures or slow movements, or where the inclination need not be determined with high accuracy during fast movements, an accelerometer is sufficient.

Duration of data collection (battery life requirement)
If highly accurate data are needed or the expected variability in arm elevation between subjects is high, data collection over many hours or even more than one day may be required (see data collection strategy in Chapter 7). Since battery capacity differs between systems, it is important to consider this factor.

Project budget and number of subjects
The project budget in relation to the number of subjects is another factor to be considered. The required number of subjects depends on the aim of the project and the related data collection strategy (see Chapter 7 for a comprehensive description). If a large project budget is available, both an accelerometer and IMU can be purchased, regardless of the number of subjects needed. If a large sample size is required and the project budget is limited, an accelerometer should be prioritized.

Need for access to the raw data
Whether access to the raw data is required depends on the research question of the project and the method to be used for analyses. In the case of a risk assessment, this depends on the guidelines used and the variables in these guidelines. If the system returns the parameters of interest, no raw data access is required. Depending upon the guidelines however, the output parameters of individual systems may not match the variables needed. Access to raw data is therefore often required. In this case, a system must be selected that offers this possibility, irrespective of the general type of system (accelerometer or IMU).

Table 6.4 provides support in choosing the system best suited to a particular project addressing arm elevation. The table requires users to check the particular requirements of their project and the feasibility of an accelerometer and IMU before selecting a particular system. The left side of the matrix lists factors that need to be considered. Three levels are given for each factor, ranging from low requirements to high requirements. The user must select the specific level of requirements per factor. The rows present ratings of the two categories of systems: “+” = recommended, “o” = partially recommended and “-” = no recommendation“. The selected system should be rated at least “partially recommended” or “recommended” for all of the main factors to be measured. If this is not the case, the user should consider modifying the requirements of the system, changing the aim of the project or using another system to better meet the requirements.

Table 6.4: Study requirements and recommendations for choosing an accelerometer or IMU according its characteristics; "-" = no recommendation; "o" = partially recommended; "+" = recommended

Requirements		Accelerometer	IMU
Output accuracy	Low accuracy	+	+
	Moderate accuracy	o	+
	High accuracy	-	+
Measurement duration, battery economy	≤1 working day	+	+
	2-3 working days	+	o
	4≤ working days	+	-
Project budget and number of subjects	Low budget, low number of subjects	+	+
	Low budget, high number subjects	+	-
	High budget	+	+

Besides the choice of general type of system (accelerometer or IMU), additional documentation with video or self-reports must be considered. Further, it must be considered whether multiple sensors should be used, if for example arm elevation in relation to the trunk or the whole body posture is relevant.

6.5 Key messages – measuring systems and analyses

Several sensor technologies for measuring arm elevation exist, among which accelerometers and IMUs are the most common.

Accelerometer-based systems may overestimate angles and angular velocities during rapid movements, whereas IMU-based measurements are likely to be more valid in this case.

For practical day-to-day work purposes, easy-to-use inexpensive methods are available that yield parameters equal in quality to those in many scientific studies. Highly accurate IMU-based systems also exist, which may be used by researchers when near-laboratory-standard data quality is required in field measurements.

Relevant variables from the arm elevation time-line are the occurrence and timing of periods, with extreme and neutral positions as well as angular velocity variables. As exposure-outcome associations are not yet fully determined, we propose that an extensive selection of possible variables be used and reported.

In order for an appropriate system to be selected, it is important that consideration be given to the aim of the study and several criteria related to this aim, i.e. the required output accuracy, duration of measurements and number of subjects in relation to the available budget.

7 Data collection strategies

Other parts of this report are devoted to identifying optimal instrumentation and proper analysis procedures for assessing arm elevation; emphasis is placed upon relevance, validity, accuracy, feasibility, and budget. An equally important factor in determining the quality of the eventual result is the data collection strategy, i.e. how sampling of data is organized [97]. Often, this ultimately means selection of the number of subjects and number of days per subject in the eventual data set and, where data collections do not cover full working days, the number of measurements per day [98-100].

Since not all subjects behave in the same way, and since not all working days take the same form [38, 86], results based on limited samples will inevitably be associated with uncertainty or "random" error, as opposed to systematic errors or bias. Bias may occur if, for instance, subjects or days are not representative for the population they are intended to typify, or if measurement methods do not provide accurate results [101]. The measurement instrument *per se* may also contribute to the uncertainty of the eventual result, one example being that observers may differ considerably in their ratings of the same working postures [65, 67, 101-103]. Contrary to observations, wearable instrumentation for posture assessment is usually regarded as being associated with negligible random error in use [51, 82], even though some technologies, such as accelerometers embedded in smart clothes, may show notable errors [104].

The statistical performance of a data collection strategy is directly related to the variability in exposure between and within subjects, and to the measurement effort in terms of the number of sampled subjects, days and measurements per day. Lower variability and more samples lead to greater precision, i.e. a result that is more likely to be close to the truth (provided that data are valid and unbiased). Variability between subjects and days can be expressed in terms of variance components, showing the contribution of each individual source of variability to the overall dispersion (uncertainty) in data [105]. Variance components can be extracted from a data set using standard statistical techniques such as ANOVA [99] and REML procedures [106], provided that multiple measurements are available on each level of interest, e.g. subjects and days. Some occupational studies have reported basic descriptive statistics on between-subject and within-subject sources of variability in arm postures in different occupational settings, [38, 48, 86, 98, 107, 108]. These studies may provide an idea of approximate magnitudes of overall variance in settings similar to those addressed by the studies. Since, however, between-subject and within-subject variabilities, even for a particular variable such as the percentage of time with the arm elevated to more than 60°, depend substantially on population and occupational setting, it is often advisable to conduct a pilot study to obtain study-specific variance component estimates prior to designing a full-scale data collection. This will assist in ultimately arriving at an appropriate study design that can deliver results of reasonable trustworthiness.

For studies aiming at determining the mean exposure in a group of subjects, well-established equations express the relationship between variance components and sample sizes, and the precision of the eventual result [109]. Based on these theoretical equations [99, 107, 110, 111], or on computer-intensive empirical simulation techniques [98, 100, 112-115], considerable research has been devoted to determining sufficient sample sizes for different purposes, different occupational exposure variables, and different occupational settings. To our knowledge, however, little support has been made available so far for the selection of appropriate sampling strategies for arm elevation measured by means of wearables. One study discussed the statistical properties of posture percentiles, which have been used extensively to describe arm elevation [116]. The study showed that percentile estimates can be biased if based on short samples, and recommends that postures should instead be expressed in terms of essentially unbiased variables such as the proportion of time spent in different angle intervals. However, variables expressing proportions or percentages of a full working day pose other challenges, inasmuch as they inherently add up to a constrained total, such as 100%. Data of this nature are "compositional" [117], and behave differently from data that are not constrained and do not add up to a constant sum, with consequences for sample size calculations and statistical testing [118]. Future research will likely address the relative occurrence of arm postures in this context, inspired by similar data in other scientific areas [119-121]. To date, however, only sporadic attention has been paid to the compositional nature of variables addressing physical load [122-124].

As discussed above, the sample sizes necessary for obtaining a specified statistical performance, for instance in terms of the size of a confidence interval on an estimated group mean value of arm elevation, strongly depend on the variability in postures between and within subjects, which, in turn, depends on the occupational context. Issuing explicit numeric guidelines on sample sizes intended to be generally applicable to all studies of arm elevation is not therefore warranted. However, some support in decision-making is provided by the generic equations expressing statistical precision as a function of variance components and sample sizes. These equations predict for example that a given total sample size, for instance 50 measurement days, will always yield a a more precise ultimate mean value across samples if they are distributed "widely" among subjects (Samuels et al. 1985); collecting data for 1 day in each of 50 subjects leads to greater precision of the mean than collecting data for example for 5 days in each of 10 subjects. The equations also convey that the marginal effect on precision of adding a further worker or day to a data set decreases with the size of the material. For example, adding 5 workers to a data set already containing 5 workers will decrease the variance of the mean to half its original size (SD reduced by 29.3%), whereas adding 5 workers to an existing 15 will reduce variance by only 25% (SD by 13.4%). The theoretical equations are valid under a number of assumptions, including that data for different workers, days and measurements within days are independent. This may not be true, one example being that exposures close in time during a working day are likely to be correlated to a larger extent than exposures further apart [98, 125]. In the event of correlation, more data are needed to arrive at a particular precision of the mean than predicted by theoretical equations [98].

The discussion above addresses issues related to the statistical performance of data collection strategies, but does not consider costs associated with sampling. Little research has been devoted to understanding and designing measurement strategies in the context of the basic trade-off between cost and precision, i.e. that a greater number of measurements leads to results of a better quality, whilst also being more expensive [73, 126, 127]. This lack of evidence is surprising, considering that assessments of cost-efficiency are necessary in order for answers to be obtained to such obvious questions as "What is the cheapest possible strategy that can still produce information of a specified quality?" and "Which one of a number of alternative data collection strategies that entail the same cost leads to greater precision of the eventual result?". Research into cost-efficient data collection *per se* is still in its infancy, quite apart from cost-efficiency studies of specific relevance to working postures. However, generic equations are available for assessing the trade-off between cost and statistical performance in some study designs, including how to optimally allocate samples to days and subjects during assessment of a group mean exposure [128]. These equations show that the “rule” stated above of the best statistical performance being obtained by distributing a certain total number of measurements among as many subjects as possible may no longer be valid if costs are also considered. Thus, if additional measurement days are cheap and additional subjects expensive, and at the same time, exposure variability between days is large compared to exposure variability between subjects, it follows that the greatest possible statistical precision at a specified total cost may be obtained with a data collection strategy directed towards many days per subject rather than many subjects, each with few days.

Notably, the relative cost-efficiency of basic approaches to obtaining information on arm elevation, i.e. questionnaires versus observation versus instrumentation, will change as the cost of applying each of these approaches changes [73]. Since wearables are likely to become even cheaper, this development will probably favour wearables, even from a cost-efficiency point of view. However, an intriguing alternative option is to predict data collected using wearables by models based on particularly cheap information, such as administrative records [129]. In some cases, such models may offer sufficient statistical performance to be attractive in terms of cost-efficiency, but very little research, if any, is available at this point to aid in deciding when modelling is affordable. Considering the significance of designing data collection strategies for upper arm postures that can deliver sufficiently informative data at minimal cost, we emphasize this as a topical issue for future research.

The above examples and discussions apply in particular to studies addressing the mean exposure of a group of subjects. The concerns of other study designs may differ, for instance as to the allocation of data samples to days and subjects, and to the volume of data required for satisfactory performance. Thus, in epidemiological studies investigating associations between exposure and outcome, associations will be attenuated if analyses are based on uncertain individual exposures [130, 131]. In this case, an informed exposure sampling strategy may prioritize repeated measurements on individual subjects to a larger extent than in studies focusing upon group mean exposures [132]. Another example is that studies specifically addressing exposures of individual subjects (such as during verification of whether a particular worker has benefited from a new workstation or a different working technique) may require repeated samples on the subjects concerned in order for sufficient precision to be attained [115]. An extensive discussion of sampling strategies in a variety of study designs is beyond the scope of this report.

7.1 Key messages – data collection strategies

For groups and individuals alike, estimates of arm elevation will be associated with uncertainty due to differences in work tasks and working technique between subjects and, for a particular subject, differences in tasks and behaviour between and within days.

Estimating arm elevation by observation further increases the uncertainty, since ratings vary both between and within observers. For direct technical measurement of arm elevation however, this additional uncertainty contributed by the measurement method may be negligible in most cases.

The uncertainty of an arm elevation estimate will be lower in situations where differences (variances) between and within subjects are small, and will decrease if more data are collected. The specific size of a data set needed to achieve a certain performance thus depends on the size of the components contributing to exposure variance.

As a rule, uncertainty is lower, i.e. precision greater, when a given number of measurements is distributed among more subjects (i.e. fewer data per subject), and – within subjects – among more days (i.e. fewer data per day). The favourable effect on precision of adding further data to an existing data set decreases with the volume of the material.

The preferable data collection strategy and also the preferable method of obtaining arm elevation data also depends on the costs associated with sampling and processing data. A more uncertain method may for example be more cost-efficient than a less uncertain alternative if the former is considerably cheaper in use. The trend towards direct instrumentation of increasingly lower cost favours cost-efficiency of direct measurements over posture observation.

8 Comparison of arm elevation at work to guidelines

One purpose of performing arm elevation measurements is risk evaluation, or in simple terms, in order to establish whether there is anything to "worry about". Use of guidelines allows researchers to translate exposure variables measured by technical means (quantitative results) to qualitative evaluations, i.e. "a low risk of physical complaints, no action is needed"; "a high risk of physical complaints, preventive measures are needed". This chapter provides a limited overview of guidelines that could be used to interpret arm elevation at work. However, our objective here is not to recommend a specific guideline.

As described earlier, many variables expressing aspects of arm elevation exposure can be calculated from time-lines of arm elevation measured by technical means. These variables can all be used in comparisons of different conditions, e.g. different tasks, jobs, or working conditions. A major challenge however is that few of the variables match available standards and guidelines (see Appendix B).

It should be noted that the guidelines suggested in ISO and EN standards are based on a consensus of experts, and that the numeric characteristics of postural angles or time aspects are not set on the basis of epidemiological evidence [133]. The selection of elevation angles in scientific studies and their subsequent inclusion in guidelines dates back to the era of visual observations. In visual observation, it is easy to divide the straight angle into two or three approximately equal parts. The convention in which the decimal system is used has transformed the measures into expressions of 45°, 30°, 60° or 90°, which are generally assessed with sufficient precision. However, other angles stated in guidelines, such as 10° or 20°, are more difficult to observe accurately.

This means that the numeric risk limits in the guidelines are based on less detailed and less accurate measures than those obtained with the use of technical devices. The figures stated in standards should therefore be interpreted with care, and not used directly as strict cut-off-points for decisions based on technical measurements.

8.1 Guidelines for observational data

With consideration for the aforementioned limitations, ISO and EN standards dealing with ergonomics and human physical performance may be used, but with great care, where exposure data from technical measurements are available.

A short summary of the standards and guidelines most relevant to arm elevation at work is provided below.

ISO 11226: Static working positions

Adopting the same unfavourable working posture for a prolonged period can lead to pain and fatigue. ISO 11226 [134] has been drawn up to assess and evaluate the biomechanical/physical load of static working postures, without external applied forces, for example involving the use of tools and lifting/pushing/pulling products. The standard provides guidelines for the physical load upon the trunk, neck, shoulder, arm and hand.

In the first step, the joint angle for each of these body regions is considered in order to assess whether it is acceptable for almost all healthy adults. This is a measure for the strain upon passive structures. In the second step, the duration for which the same posture is maintained is considered:

this takes static muscle load into account. Duration limits correspond to 20% of the maximum holding time, which can be estimated by a discomfort/pain score of 2 on a visual analogue scale (0-10). Each effort must be followed by a recovery time. The guidelines for shoulder load will be discussed in more detail.

To determine the shoulder load, arm elevation between the vertical line and the line passing through the acromion-clavicula and humerus-radius joints must be assessed. The elevation movement of the upper arm during the working posture is compared with the reference posture.

Table 8.1. Assessment table for static arm elevation (based on [134])

Arm elevation	Duration
20° - 20° (extension-flexion)	Acceptable
20 - 60° (flexion), with full arm support	Acceptable
20 - 60° (flexion), without full arm support	Maximum acceptable holding time 20°: 4' 40°: 2'30 60°: 1'
> 60°	Not recommended
Awkward upper arm postures, e.g. extension (>20°), adduction, extreme external rotation, elevated shoulders	Not recommended

EN 1005-4: Working positions and movements

By analogy with the ISO 11226 standard for static working postures, EN 1005-4 [135] involves analysis of each joint/body region. The model of health risks associated with postures and movements is parabolic (Figure 8.1), reflecting that risks are elevated both with too little and too much movement.

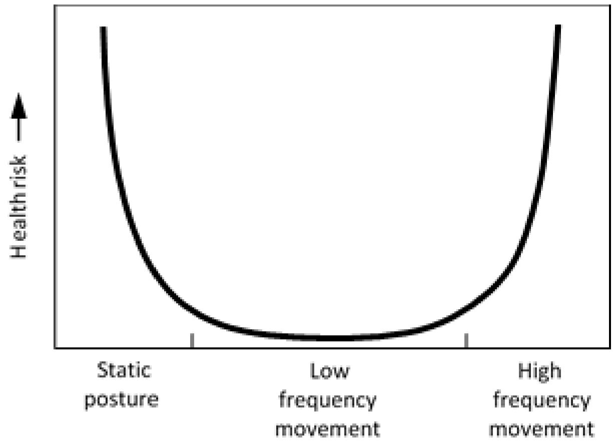

Figure 8.1. Model for postural and physical health risks (based on [135])

The evaluation of the shoulder load employs the same categories of arm elevation as ISO 11226. Instead of total duration, static and dynamic loads are considered, as indicated in Table 8.2.

Table 8.2. Assessment table for static and dynamic arm elevation (based on [135])

	Static (>4 sec)	Dynamic (<2/min)	Dynamic (>2/min)
0 - 20° (flexion)	Acceptable	Acceptable	Acceptable
20 - 60° (flexion)	Conditionally acceptable*	Acceptable	Conditionally acceptable***
> 60° (flexion)	Not acceptable	Conditionally acceptable**	Not acceptable
< 0° (extension)	Not acceptable	Conditionally acceptable**	Not acceptable

* Acceptable if full arm support is provided; if it is not, acceptability depends upon the duration of the posture and period of recovery.

** Not acceptable if the machine may be used for long durations by the same person.

*** Not acceptable if frequency is ≥ 10/min or if the machine may be used for long durations by the same person.

ISO 11228-3: Repetitive work

ISO 11228-3 governing repetitive work [136] proposes two methods for evaluation of the risk. The simple method employs a checklist of the following factors: repetitiveness, force exertion, recovery periods and additional factors.

When the risk as evaluated according to this checklist is found to be in the yellow or red zone (traffic light scheme), a more in-depth analysis is needed. For this analysis, several simple observational methods and checklists already referred to may be used, i.e. OWAS, RULA, REBA or the OCRA index (see Chapter 5.2).

Limits used in observational assessment methods

Table 8.3 provides an overview of the limits for arm elevation stated in different assessment methods. Some methods describe the arm postures only verbally, but most methods state explicit angle ranges for assessment of arm elevation.

Table 8.3. Arm elevation angle limits used in observational assessment methods

Assessment method	**Limits for arm elevation (angle ranges in order of severity, low to high)**
OWAS [54]	Arm(s) shoulder height (>90°)
RULA [57]	Upper arms: 20°-20° (extension-flexion); >20° extension; 20-45°; 45-90°; >90°
REBA [56]	As RULA
OCRA [58, 59]	Movements of upper arm in front of/beside the body
LUBA [60]	Flexion: 0-45°; 45-90°; 90-150°; >150° Extension: 0-20°; 20-45°; 45-60°; >60° Adduction: 0-10°; 10-30°; >30° Abduction: 0-30°; 30-90°; >90°
QEC [55]	Hands: at or below waist height; at about chest height; at or above shoulder height
HARM [61, 62]	Flexion/abduction: percentage of time above 30°

The overall outcomes of some assessment methods (OCRA and HARM) have been validated by means of epidemiological data [62]. However, none of the methods and limits have been validated specifically for arm elevation. Recent attempts to validate limits for arm elevation by means of epidemiological data have returned inconsistent results [23, 137].

8.2 An epidemiologically based guideline for technical measurements

Occupational and Environmental Medicine at Lund University, Sweden has collected more than 1,000 technical measurements of workers in around 60 different occupations over 30 years, by methods including electromyography, inclinometry and goniometry. The prevalence of MSDs in the occupational groups studied was determined at the same time by means of a standardized clinical method [138]. These data enabled associations between arm postures and MSDs to be determined. This resulted in exposure-response relationships being published for disorders in the neck/shoulder [20] and elbow/hands [139]. Based on collected data, analyses of exposure-response relationships, evidence from the scientific literature and the overall experience of the research group, load action levels have been proposed for arm postures and movements at work [140]. The following action levels have been proposed for the upper arm, based on accelerometer measurements:

- Median load (50th percentile), i.e. the exposure exceeded for half of the total working day. **Movement velocity, Upper arm: 60 °/s**
- Peak load (90th percentile), i.e. the exposure exceeded for ten percent of the total working day. **Posture, Elevated upper arm: 60 °**

8.3 Future demands

The action limits proposed by Arvidsson et al. [140] may constitute an important step towards guidelines supported by epidemiologic evidence. However, a need still exists for more quantitative data on exposure to arm elevation at work and the associated health outcomes. One of the goals of this report is to call for the collection of specified data in a harmonized way, with the possibility of combining data for use in the development of more scientifically based standards and guidelines.

8.4 Key messages – comparison to guidelines

Guidelines may be used to interpret exposure variables measured by technical means for the purposes of a risk assessment, provided that certain limitations are taken into account.

The available ISO and EN standards concerning arm elevation are guidelines for observational methods. They are consensus-based, developed by experts sharing scientific knowledge.

Limits for arm elevation angles from observational assessment methods range from 20-150°, with severity of shoulder load growing with increasing angles. None of these limits is validated.

Lund action levels are a guideline for technical measurements, based on large-scale epidemiological research using accelerometers to measure arm elevation. More epidemiologically based guidelines are needed.

9 Scenarios

Chapter 6.4 describes criteria to be considered during selection of a suitable system for measuring arm elevation. This chapter illustrates the application of different systems for different study purposes with reference to several examples. The aim of a project may be to evaluate:

1. whether arm elevation constitutes a risk for the development of MSDs in a specific job or work task (*risk assessment at the group level*);
2. the effect or cost-effectiveness of an intervention to reduce arm elevation at work (*interventions at the group level*);
3. whether arm elevation constitutes a risk for the development of MSDs for a particular worker, e.g. for insurance purposes (*risk assessment at the individual level*);
4. arm elevation at work at the individual level, for instance in order to provide feedback and raise awareness on physical workload and/or motivate the person to change behaviour (*interventions at the individual level*).

Examples of likely scenarios in these categories are presented below, with particular focus on the selection of measurement device(s) and data collection strategy. The examples are focused on the minimal requirements for the assessment of arm elevation and other exposures. Use of more sensors for longer time periods so as to obtain even better data or to add additional output variables could be considered depending on the aim and scope of the project.

9.1 Risk assessment at the group level

Scenario a)

Fruit picking occurs periodically for a limited time in season; the work is then mostly intensive and often overhead, however. A researcher seeks to determine whether exposure to arm elevation during fruit picking is associated with acute shoulder pain and whether reported pain is related to the intensity of work and the working technique (expressed in terms of rest, arm velocity etc.). For this project, the researcher requires representative information on daily activities/exposure outside the picking season and daily activities/exposure during the season. If the exposure patterns among the workers are reasonably consistent both during and outside the season, it may be sufficient to evaluate exposure for a week or less during both periods. Both continuous and working-day measurements may be performed. The main variable to be measured is the elevation of the upper arms during standing, and specifically, the duration of extreme arm elevation (>90°), “time at rest” (arm elevation <20° and arm elevation velocity <5°/s) and median velocity of arm elevation (see list of variables in Appendix A). This requires a system that measures the inclination of both arms and that can distinguish standing from other postures. The required information can be supplied by a minimum of three sensors (accelerometer/inclinometer), mounted on both upper arms and on one thigh. Questionnaires or diaries may be used to assess other risk factors, and also outcomes such as pain. Linking the objective information on the total duration and temporal pattern of arm elevation during work to the pain reports, both in and out of season, enables the study questions to be answered.

Scenario b)

After a change of operation, tailgate cable harness assemblers often experience symptoms of overuse of the shoulder joint. The cable harnesses are mainly fitted overhead on the tailgate with the assembler adopting an upright posture. The joint loads resulting from forced posture are considered problematic. The ergonomist of the company is commissioned to point out unfavourable upper arm postures during assembly, in order to permit development of possible improvements to the work process. The analysis is intended to provide information on cumulative durations of arm elevation levels exceeding 60°, 90° and 120° and on durations of uninterrupted arm elevation levels above 60° and 90° during a typical work shift. Since the assemblers work in an upright posture, the examiner needs a simple sensor (accelerometer/inclinometer) with which the upper arm position can be determined with respect to the vertical line. It is sufficient for data to be collected from the dominant arm, since it performs the main assembly tasks. Since the work processes are recurring and short-term (approx. 90 seconds per cycle), a one-hour measurement contains sufficient repetitions to provide a representative indication of the load in this assembly task. As the ergonomist remains on site, he can check that the arm elevation is measured during the assembly work. With the aid of the results, he can determine the load peaks and, if necessary, consider possible improvement measures.

Scenario c)

Surgeons may be exposed to work with elevated arms in combination with requirements for precision. Such static demands can lead to complaints in the shoulder-neck area. In order to address complaints-related failures preventively, the safety and health personnel of a hospital are commissioned to quantify the arm elevation in surgeons. They aim to investigate the arm elevation characteristic over time and in particular the duration and distribution of periods with very low variation for representative subjects in this occupational group. In this case, accelerometer-based systems with internal loggers may be selected. Since the surgeons' work tasks can be very heterogeneous, measurements should preferably be carried out during the entire working day, and not only during one patient case. If every subject is observed during the measurement, the observer can determine whether or not the weight of the arm is supported. This information should be combined with the measurement data. Specific subtasks can then be identified as being particularly exposed, and prioritized during ergonomic interventions.

9.2 Interventions at the group level

Scenario d)

The work of hairdressers involves extensive arm elevation, which may be associated with a high biomechanical workload in the neck and shoulder region. Recommendations are available for changing the working technique in order to reduce this load, for example by reducing work with the arms elevated wherever possible, taking breaks as often as possible, checking arm postures in the mirror while working, etc. A researcher is asked to investigate whether time spent at work with the arms elevated could be reduced by providing simple information giving working technique recommendations. The purpose of the study is to describe and analyse the effect of two different intensity levels of the intervention on the daily duration of arm elevation >30°, >60° and >90° during work. Level 1 of the intervention comprises written information only, level 2 includes additional personal follow-up. The hairdressers are to be randomized between the two different intensity levels of the intervention. Arm elevation during work is to be assessed on both upper arms with a simple sensor on 2-3 working days before the intervention and 2-3 working days after 1 to 2 months. An additional observation could permit distinction between different tasks. For evaluation of long-term effects on working technique, a longer follow-up time is necessary (e.g. 6 months). This enables the researcher to compare the effects of both interventions on the total duration of arm elevation in different angle ranges. Investigation of the cost-effectiveness of the interventions is also conceivable at this point.

Scenario e)

Many pavers have problems reaching retirement age without musculoskeletal symptoms. Symptoms are often located in the shoulder and neck area. Before introducing paving by machine as a solution to manual paving, the industry commissions researchers with testing the extent to which machine paving would in fact reduce the risk of MSDs. The aim of the study is therefore to investigate whether machine paving is effective in reducing the risk level caused by physical work demands (including arm elevation) associated with manual paving.
For this project, the researchers require a system that can assess not only arm elevation but also whole body postures, for both machine and manual paving, and evaluate them based on guidelines for physical workload. Even small postural differences may be relevant; the accuracy of output variables must therefore be high. Since manual paving often involves working with the trunk inclined, recording of arm elevation angles with respect to the trunk (local arm elevation angles) must be possible in addition to global arm elevation angles. Furthermore, it may be useful for a detailed analysis to distinguish between flexion/extension and abduction/adduction angle, since for example different muscles are loaded depending on the direction of movement. Simulation of the work in an experimental, controlled environment in which a limited number of subjects can perform both machine and manual paving, thereby serving as their own controls, results in the measurement duration and battery requirements being low. The paving task has a short cycle time (<1 min). A measurement duration of 30 minutes yields up to 50 repetitions of the specific postures and movements, providing a good indication of the average postural angles and their variation. The research question requires the application of a multi-sensor expert system to record working postures and movements in detail. This enables the researchers to gain information on the total duration and temporal pattern of arm elevation and other body angles. From the angle time-line, the frequency and duration of periods of arm elevation within specified angle ranges, for example above 20° or above 60°, can be calculated. These results can be extrapolated to a full working day and the results for the two conditions can then be compared.

Scenario f)

Many employees at a manufacturing plant have developed musculoskeletal complaints. Five workstations are present, two of which require overhead work and work with outstretched arms. The remaining three workstations require handling of heavy loads, forklift driving and product inspection. The company's aim is to investigate whether job rotation would be an effective intervention for a more balanced distribution of physical workload among workers in this production segment.
This project requires a measuring system capable of assessing the differences in the workload of the different workstations, including differences in posture and movement of both individual body parts and the whole body during the course of the working day. In this case, the assessment of as many aspects as possible is desirable, e.g. body posture distributions, repeated movements, speed of

movements and muscle activity. A measuring system employing multiple motion sensors positioned on the trunk and extremities on each side of the body permits assessment of individual body part orientation and movement (including trunk flexion and arm elevation). EMG could provide information on relevant muscle activation. To assure exact assignment of the physical demands to activities, a video should be recorded simultaneously that can be synchronized with the sensor data. In order to assess kinematic and physiological properties of each of the workstations, measurements over 1-3 working days, each of 4-8 hours per workstation, may be sufficient.
Based on this data, a very precise analysis of the loads of individual body regions at the five stations is possible. This permits evaluation of whether job rotation could be a beneficial measure for better workload distribution, and of which stations could ideally be combined with each other, the proposal being to simulate different combinations of work at the five stations at different times.

9.3 Risk assessment at the individual level

Scenario g)

A professional painter seeks medical help due to pain in the neck and shoulder experienced during work. Work above shoulder level, e.g. painting ceilings, is problematic and increasingly difficult to perform. The clinical examination is performed using standard methods such as anamnesis and physical examination and a diagnosis is confirmed. In order to establish a probable relationship between exposure during work and the complaints, e.g. for the purpose of insurance claims, additional information is required. This could be obtained from objective technical measurements of the physical load and their relation to guidelines of harmful exposure (action levels).
The examiner uses an inclinometer with integrated data logger to perform measurements during three full working days. Measurement is performed on a colleague of the patient who is exposed to the same workload, as data must be obtained from work that is not restricted by pain and other health-related issues. Data analysis is then performed and relevant output variables presented in relation to the relevant action levels. Should the results show that the recommended levels are exceeded, grounds exist for the assumption that the complaints experienced by the patient can, to some extent, be explained by exposures at work.
The examiner can view the patient’s condition as a sign that the working conditions could be harmful. The obtaining of objective data, relating them to action levels, and implementing effective initiatives to lower the exposure may therefore prevent colleagues from sustaining injury.

9.4 Intervention at the individual level

Scenario h)

The prevalence of MSDs in manual work is generally high. Assembly work is one example with a high prevalence of shoulder disorders, especially among women. Repetitive tasks, in particular in conjunction with high force requirements, are likely to contribute to the high prevalence; the workload also depends on the technique of the individual, however. As in any occupation, different workers may perform the work tasks in different ways. By using feedback to train the workers, exposures may be reduced.
In order to achieve a good working technique in terms of arm postures and movements, direct feedback to the worker should be used. Measurements could be performed with IMUs attached to the upper arms and connected to a smartphone using Bluetooth. By calculating variables over the duration of a work cycle that can be compared to eight-hour action levels (assuming that the worker

works similarly in all cycles), alerts can be issued to the workers in the event of action limits being exceeded. These warnings can be issued in visual, auditory or tactile form. Introduced at an early stage of employment, this can be a good means of establishing optimal habits. The feedback sessions may be repeated for example on three working days. Should the variables under consideration still be above the action levels even after the feedback sessions, other organizational and/or technical measures should be considered.

10 Discussion

This report provides practical guidance on technical methods for assessing arm elevation at work for researchers and practitioners, comprising selection of a suitable device and sampling strategy and interpretation of the measurement results. The report recommends the use of technical methods that allow simple and accurate field measurement of arm elevation. The recommendations stated have been agreed by consensus between several research teams with expertise in the application of technical exposure assessment systems. They are also intended as a call for more frequent and harmonized application of technical measurements for investigation of the association between arm elevation and health outcomes, the results of which should serve as a basis for the deriving of new prevention guidelines.

On the one hand, the technical systems presented in this report build on current practice and existing technical systems. However, the possibilities for straightforward measurement of arm elevation at work are increasing dramatically. The *approach* to selection, use, analysis of data and interpretation of the results of technical measurements will therefore be of great importance for both researchers and practitioners in the future.

On the other hand, arm elevation is a proxy measure of biomechanical load imposed on the shoulder. Other factors causing biomechanical shoulder loading also exist, in particular the position of the forearm and additional forces caused by hand-held or manipulated weights. Should these determinants not be considered, a risk exists of potential bias in the interpretation of measurement results. This concerns risk assessment studies of groups and individuals alike. To reduce this bias, systems will be required in future that are capable of easily measuring the position of the arm and forearm, and also the weights and forces manipulated in the hand. These measurements can then be used as input for a biomechanical model of the upper limb, and the output will more fully reflect the biomechanical load on the shoulder.

11 References

1. Armstrong, T.J., P. Buckle, L.J. Fine, M. Hagberg, B. Jonsson, Å. Kilbom, I.A.A. Kuorinka, B. Silverstein, G. Sjøgaard, and E.R.A. Viikari-Juntura, *A conceptual model for work-related neck and upper-limb musculoskeletal disorders.* Scand J Work Environ Health, 1993. **19**(2): p. 73-84.
2. Kumar, S., *Theories of musculoskeletal injury causation.* Ergonomics, 2001. **44**(1): p. 17-47.
3. Hägg, G.M., *Static work loads and occupational myalgia - a new explanation model*, in *Electromyographical kinesiology*, P.A. Anderson, D.J. Hobart, and J.V. Danoff, Editors. 1991, Elsevier Science Publishers B.V.: Amsterdam. p. 141-144.
4. Visser, B. and J.H. van Dieën, *Pathophysiology of upper extremity muscle disorders.* J Electromyogr Kinesiol, 2006. **16**(1): p. 1-16.
5. Barbe, M.F. and A.E. Barr, *Inflammation and the pathophysiology of work-related musculoskeletal disorders.* Brain Behav Immun., 2006. **20**(5): p. 423-429.
6. Palmerud, G., M. Forsman, H. Sporrong, P. Herberts, and R. Kadefors, *Intramuscular pressure of the infra- and supraspinatus muscles in relation to hand load and arm posture.* Eur J Appl Physiol, 2000. **83**(2-3): p. 223-30.
7. Seitz, A.L., P.W. McClure, S. Finucane, N.D. Boardman, 3rd, and L.A. Michener, *Mechanisms of rotator cuff tendinopathy: intrinsic, extrinsic, or both?* Clin Biomech (Bristol, Avon), 2011. **26**(1): p. 1-12.
8. Hultman, E. and H. Sjöholm, *Blood pressure and heart rate response to voluntary and nonvoluntary static exercise in man.* Acta Physiol Scand, 1982. **115**(4): p. 499-501.
9. Schumann, B., A. Seidler, A. Kluttig, K. Werdan, J. Haerting, and K.H. Greiser, *Association of occupation with prevalent hypertension in an elderly East German population: an exploratory cross-sectional analysis.* Int Arch Occup Environ Health, 2011. **84**(4): p. 361-9.
10. Bernard, B.P., *Musculoskeletal disorders and workplace factors. A critical review of epidemiologic evidence for work-related musculoskeletal disorders of the neck, upper extremity, and low back*. 1997, Cincinnati, OH: U.S.: Department of health and Human Services, NIOSH.
11. Walker-Bone, K.E., K.T. Palmer, I. Reading, and C. Cooper, *Soft-tissue rheumatic disorders of the neck and upper limb: prevalence and risk factors.* Semin Arthritis Rheum, 2003. **33**(3): p. 185-203.
12. Jones, G.T., N. Pallawatte, A. El-Metwally, G.J. Macfarlane, D.M. Reid, and F.D. Dick, *Associations between work-related exposure and the occurrence of rotator cuff disease and / or biceps tendinitis. A reference document*. 2007: http://www.ask.dk/graphics/dokumenter/pdf/forskning/udredningsrapport_skulder_og_overarm.pdf.
13. van der Molen, H.F., C. Foresti, J.G. Daams, M.H.W. Frings-Dresen, and P. Kuijer, *Work-related risk factors for specific shoulder disorders: a systematic review and meta-analysis.* Occup Environ Med, 2017. **74**(10): p. 745-755.
14. Mayer, J., T. Kraus, and E. Ochsmann, *Longitudinal evidence for the association between work-related physical exposures and neck and/or shoulder complaints: a systematic review.* Int Arch Occup Environ Health, 2012. **85**(6): p. 587-603.
15. van Rijn, R.M., B.M. Huisstede, B.W. Koes, and A. Burdorf, *Associations between work-related factors and specific disorders of the shoulder--a systematic review of the literature.* Scand J Work Environ Health, 2010. **36**(3): p. 189-201.
16. Ariens, G.A., W. van Mechelen, P.M. Bongers, L.M. Bouter, and G. van der Wal, *Physical risk factors for neck pain.* Scand J Work Environ Health, 2000. **26**(1): p. 7-19.
17. Veiersted, B., S. Knardahl, and M. Wærsted, *Mekaniske eksponeringer i arbeid som årsak til muskel- og skjelettplager - en kunnskapsstatus*, in *STAMI-rapport*. 2017, Statens arbeidsmiljøinstitutt: Oslo. p. 1-102.
18. Svendsen, S.W., A. Dalbøge, J.H. Andersen, J.F. Thomsen, and P. Frost, *Risk of surgery for subacromial impingement syndrome in relation to neck-shoulder complaints and*

occupational biomechanical exposures: a longitudinal study. Scand J Work Environ Health, 2013. **39**(6): p. 568-77.
19. Punnett, L., L.J. Fine, W.M. Keyserling, G.D. Herrin, and D.B. Chaffin, *Shoulder disorders and postural stress in automobile assembly work.* Scand J Work Environ Health, 2000. **26**(4): p. 283-91.
20. Nordander, C., G.Å. Hansson, K. Ohlsson, I. Arvidsson, I. Balogh, U. Strömberg, R. Rittner, and S. Skerfving, *Exposure-response relationships for work-related neck and shoulder musculoskeletal disorders--Analyses of pooled uniform data sets.* Appl Ergon, 2016. **55**: p. 70-84.
21. Svendsen, S.W., J.P. Bonde, S.E. Mathiassen, K. Stengaard-Pedersen, and L.H. Frich, *Work related shoulder disorders: quantitative exposure-response relations with reference to arm posture.* Occup Environ Med, 2004. **61**(10): p. 844-53.
22. Hanvold, T.N., M. Wærsted, A.M. Mengshoel, E. Bjertness, and K.B. Veiersted, *Work with prolonged arm elevation as a risk factor for shoulder pain: a longitudinal study among young adults.* Appl Ergon, 2015. **47**: p. 43-51.
23. Koch, M., L.K. Lunde, K.B. Veiersted, and S. Knardahl, *Association of objectively measured arm inclination with shoulder pain: A 6-month follow-up prospective study of construction and health care workers.* PLoS One, 2017. **12**(11): p. e0188372.
24. Mikkonen, P., E. Viikari-Juntura, J. Remes, T. Pienimaki, S. Solovieva, S. Taimela, P. Zitting, M. Koiranen, P. Leino-Arjas, and J. Karppinen, *Physical workload and risk of low back pain in adolescence.* Occup Environ Med, 2012. **69**(4): p. 284-90.
25. Harkness, E.F., G.J. Macfarlane, E.S. Nahit, A.J. Silman, and J. McBeth, *Risk factors for new-onset low back pain amongst cohorts of newly employed workers.* Rheumatology (Oxford), 2003. **42**(8): p. 959-68.
26. Christensen, J.O. and S. Knardahl, *Work and back pain: a prospective study of psychological, social and mechanical predictors of back pain severity.* Eur J Pain, 2012. **16**(6): p. 921-33.
27. Myers, A.H., S.P. Baker, G. Li, G.S. Smith, S. Wiker, K.Y. Liang, and J.V. Johnson, *Back injury in municipal workers: a case-control study.* Am J Public Health, 1999. **89**(7): p. 1036-41.
28. Shiri, R., K.P. Martimo, H. Miranda, R. Ketola, L. Kaila-Kangas, H. Liira, J. Karppinen, and E. Viikari-Juntura, *The effect of workplace intervention on pain and sickness absence caused by upper-extremity musculoskeletal disorders.* Scand J Work Environ Health, 2011. **37**(2): p. 120-8.
29. Andersen, L.L., N. Fallentin, S.V. Thorsen, and A. Holtermann, *Physical workload and risk of long-term sickness absence in the general working population and among blue-collar workers: prospective cohort study with register follow-up.* Occup Environ Med, 2016. **73**(4): p. 246-53.
30. Sterud, T., *Work-related psychosocial and mechanical risk factors for work disability: a 3-year follow-up study of the general working population in Norway.* Scand J Work Environ Health, 2013. **39**(5): p. 468-76.
31. NOA, *Faktabok om arbeidsmiljø og helse 2015. Status og utviklingstrekk (Facts about work environment and health 2015)*. 2015, NIOH: Oslo, Norway.
32. *Statistics Sweden. Statistikdatabasen*. [cited 2017 03.15]; Available from: http://www.statistikdatabasen.scb.se/pxweb/sv/ssd/?rxid=4e5639be-b6da-4b6f-8319-ac5ccb649cce.
33. *Danmarks Statistik*. [cited 2017 03.10]; Available from: http://www.dst.dk/da/statistik.aspx.
34. Bodin, J., C. Ha, A. Petit Le Manac'h, C. Serazin, A. Descatha, A. Leclerc, M. Goldberg, and Y. Roquelaure, *Risk factors for incidence of rotator cuff syndrome in a large working population.* Scand J Work Environ Health, 2012. **38**(5): p. 436-46.
35. Perkiö-Mäkelä, M. and M. Hirvonen, *TYÖ JA TERVEYS - haastattelututkimus 2012 - taulukkoraportti*. 2013. Available from: https://www.ttl.fi/wp-content/uploads/2016/11/Tyo-ja-terveys-haastattelututkimus-2012-taulukkoraportti.pdf.

36. Tynes, T., C. Aagestad, S.V. Thorsen, L.L. Andersen, M. Perkio-Makela, F.J.P. Garcia, L.G. Blanco, G. Vermeylen, A. Parent-Thirion, W. Hooftman, I. Houtman, F. Liebers, H. Burr, and M. Formazin, *Physical working conditions as covered in European monitoring questionnaires.* BMC Public Health, 2017. **17**(1): p. 544.
37. Hansson, G.Å., I. Balogh, K. Ohlsson, L. Granqvist, C. Nordander, I. Arvidsson, I. Åkesson, J. Unge, R. Rittner, U. Strömberg, and S. Skerfving, *Physical workload in various types of work: Part II. Neck, shoulder and upper arm.* International Journal of Industrial Ergonomics, 2010. **40**(3): p. 267-281.
38. Wahlström, J., S.E. Mathiassen, P. Liv, P. Hedlund, C. Ahlgren, and M. Forsman, *Upper arm postures and movements in female hairdressers across four full working days.* Ann Occup Hyg, 2010. **54**(5): p. 584-94.
39. Veiersted, K.B., K.S. Gould, N. Østerås, and G.Å. Hansson, *Effect of an intervention addressing working technique on the biomechanical load of the neck and shoulders among hairdressers.* Appl Ergon, 2008. **39**(2): p. 183-90.
40. Moriguchi, C.S., L. Carnaz, K.B. Veiersted, T.N. Hanvold, L.B. Hæg, G.Å. Hansson, and H.J. Cote Gil Coury, *Occupational posture exposure among construction electricians.* Appl Ergon, 2013. **44**(1): p. 86-92.
41. Wiktorin, C., E. Vingård, M. Mortimer, G. Pernold, E. Wigaeus-Hjelm, Å. Kilbom, and L. Alfredsson, *Interview versus questionnaire for assessing physical loads in the population-based MUSIC-Norrtalje Study.* Am J Ind Med, 1999. **35**(5): p. 441-55.
42. Herberts, P., R. Kadefors, G. Andersson, and I. Petersèn, *Shoulder pain in industry: an epidemiological study on welders.* Acta Orthop Scand, 1981. **52**(3): p. 299-306.
43. Sakakibara, H., M. Miyao, T. Kondo, and S. Yamada, *Overhead work and shoulder-neck pain in orchard farmers harvesting pears and apples.* Ergonomics, 1995. **38**(4): p. 700-6.
44. Wu, G., F.C.T. van der Helm, H.E.J. Veeger, M. Makhsous, P. Van Roy, C. Anglin, J. Nagels, A.R. Karduna, K. McQuade, X.G. Wang, F.W. Werner, and B. Buchholz, *ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion - Part II: shoulder, elbow, wrist and hand.* Journal of Biomechanics, 2005. **38**(5): p. 981-992.
45. An, K.N., A.O. Browne, S. Korinek, S. Tanaka, and B.F. Morrey, *Three-dimensional kinematics of glenohumeral elevation.* J Orthop Res, 1991. **9**(1): p. 143-9.
46. Rab, G., K. Petuskey, and A. Bagley, *A method for determination of upper extremity kinematics.* Gait Posture, 2002. **15**(2): p. 113-9.
47. Petuskey, K., A. Bagley, E. Abdala, M.A. James, and G. Rab, *Upper extremity kinematics during functional activities: three-dimensional studies in a normal pediatric population.* Gait Posture, 2007. **25**(4): p. 573-9.
48. Hansson, G.Å., I. Arvidsson, K. Ohlsson, C. Nordander, S.E. Mathiassen, S. Skerfving, and I. Balogh, *Precision of measurements of physical workload during standardised manual handling. Part II: Inclinometry of head, upper back, neck and upper arms.* J Electromyogr Kinesiol, 2006. **16**(2): p. 125-36.
49. Viikari-Juntura, E., R. Martikainen, R. Luukkonen, P. Mutanen, E.P. Takala, and H. Riihimaki, *Longitudinal study on work related and individual risk factors affecting radiating neck pain.* Occup Environ Med, 2001. **58**(5): p. 345-52.
50. Seidler, A., U. Bolm-Audorff, G. Petereit-Haack, E. Ball, M. Klupp, N. Krauss, and G. Elsner, *Work-related lesions of the supraspinatus tendon: a case-control study.* Int Arch Occup Environ Health, 2011. **84**(4): p. 425-33.
51. Hansson, G.Å., P. Asterland, N.G. Holmer, and S. Skerfving, *Validity and reliability of triaxial accelerometers for inclinometry in posture analysis.* Med Biol Eng Comput, 2001. **39**(4): p. 405-13.
52. d'Errico, A., R. Gore, J.E. Gold, J.S. Park, and L. Punnett, *Medium- and long-term reproducibility of self-reported exposure to physical ergonomics factors at work.* Appl Ergon, 2007. **38**(2): p. 167-75.

53. Koch, M., L.K. Lunde, T. Gjulem, S. Knardahl, and K.B. Veiersted, *Validity of questionnaire and representativeness of objective methods for measurements of mechanical exposures in construction and health care work.* PLoS One, 2016. **11**(9): p. e0162881.
54. Karhu, O., P. Kansi, and I. Kuorinka, *Correcting working postures in industry: A practical method for analysis.* Appl Ergon, 1977. **8**(4): p. 199-201.
55. Li, G. and P. Buckle, *Evaluating change in exposure to risk for musculoskeletal disorders - a practical tool. HSE Contract report 251/1999*, in *HSE Contract report*. 1999.
56. Hignett, S. and L. McAtamney, *Rapid entire body assessment*, in *Handbook of Human Factors Ergonomics Methods*. 2004, CRC Press. p. 97-108.
57. McAtamney, L. and E.N. Corlett, *RULA: a survey method for the investigation of work-related upper limb disorders.* Appl Ergon, 1993. **24**(2): p. 91-9.
58. Occhipinti, E., *OCRA: a concise index for the assessment of exposure to repetitive movements of the upper limbs.* Ergonomics, 1998. **41**(9): p. 1290-311.
59. Colombini, D. and E. Occhipinti, *[Prevention and management of the risk of biomechanical work overload diseases -- evaluation of the risk, health supervision and ergonomic planning. Educational courses, 2006-2007].* Med Lav, 2005. **96**(6): p. 551.
60. Kee, D. and W. Karwowski, *LUBA: an assessment technique for postural loading on the upper body based on joint motion discomfort and maximum holding time.* Appl Ergon, 2001. **32**(4): p. 357-66.
61. Douwes, M. and H. de Kraker, *Development of a non-expert risk assessment method for hand-arm related tasks (HARM).* International Journal of Industrial Ergonomics, 2014. **44**(2): p. 316-327.
62. Douwes, M., M. Boocock, P. Coenen, S. van den Heuvel, and T. Bosch, *Predictive validity of the Hand Arm Risk assessment Method (HARM).* International Journal of Industrial Ergonomics, 2014. **44**(2): p. 328-334.
63. Takala, E.P., I. Pehkonen, M. Forsman, G.Å. Hansson, S.E. Mathiassen, W.P. Neumann, G. Sjøgaard, K.B. Veiersted, R.H. Westgaard, and J. Winkel, *Systematic evaluation of observational methods assessing biomechanical exposures at work.* Scand J Work Environ Health, 2010. **36**(1): p. 3-24.
64. Bao, S., N. Howard, P. Spielholz, B. Silverstein, and N. Polissar, *Interrater reliability of posture observations.* Hum Factors, 2009. **51**(3): p. 292-309.
65. Rezagholi, M., S.E. Mathiassen, and P. Liv, *Cost efficiency comparison of four video-based techniques for assessing upper arm postures.* Ergonomics, 2012. **55**(3): p. 350-60.
66. Trask, C., S.E. Mathiassen, J. Jackson, and J. Wahlstrom, *Data processing costs for three posture assessment methods.* BMC Med Res Methodol, 2013. **13**: p. 124.
67. Trask, C., S.E. Mathiassen, M. Rostami, and M. Heiden, *Observer variability in posture assessment from video recordings: The effect of partly visible periods.* Appl Ergon, 2017. **60**: p. 275-281.
68. DeLooze, M.P., H.M. Toussaint, J. Ensink, C. Mangnus, and A.J. van der Beek, *The validity of visual observation to assess posture in a laboratory-simulated, manual material handling task.* Ergonomics, 1994. **37**(8): p. 1335-43.
69. Spielholz, P., B. Silverstein, M. Morgan, H. Checkoway, and J. Kaufman, *Comparison of self-report, video observation and direct measurement methods for upper extremity musculoskeletal disorder physical risk factors.* Ergonomics, 2001. **44**(6): p. 588-613.
70. David, G.C., *Ergonomic methods for assessing exposure to risk factors for work-related musculoskeletal disorders.* Occup Med (Lond), 2005. **55**(3): p. 190-9.
71. van der Beek, A.J. and M.H. Frings-Dresen, *Assessment of mechanical exposure in ergonomic epidemiology.* Occup Environ Med, 1998. **55**(5): p. 291-9.
72. Trask, C., K. Teschke, J. Village, Y. Chow, P. Johnson, N. Luong, and M. Koehoorn, *Measuring low back injury risk factors in challenging work environments: an evaluation of cost and feasibility.* Am J Ind Med, 2007. **50**(9): p. 687-96.

73. Trask, C., S.E. Mathiassen, J. Wahlström, and M. Forsman, *Cost-efficient assessment of biomechanical exposure in occupational groups, exemplified by posture observation and inclinometry.* Scand J Work Environ Health, 2014. **40**(3): p. 252-65.
74. Dahlqvist, C., G.A. Hansson, and M. Forsman, *Validity of a small low-cost triaxial accelerometer with integrated logger for uncomplicated measurements of postures and movements of head, upper back and upper arms.* Appl Ergon, 2016. **55**: p. 108-116.
75. Ericson MO, Heijdenberg J, and W. K, *Abduflex - Portable system for field measurements of arm postures and motions. Technical report. TRITA-IMA, 94:4, ISSN 1104-2656*. 1994.
76. Wiktorin, C., M. Mortimer, L. Ekenvall, A. Kilbom, and E.W. Hjelm, *HARBO, a simple computer-aided observation method for recording work postures.* Scand J Work Environ Health, 1995. **21**(6): p. 440-9.
77. Fernstrom, E.A. and M.O. Ericson, *Upper-arm elevation during office work.* Ergonomics, 1996. **39**(10): p. 1221-30.
78. Aarås, A., R.H. Westgaard, and E. Stranden, *Postural angles as an indicator of postural load and muscular injury in occupational work situations.* Ergonomics, 1988. **31**(6): p. 915-33.
79. Aarås, A. and E. Stranden, *Measurement of postural angles during work.* Ergonomics, 1988. **31**(6): p. 935-44.
80. Hansson, G.A., P. Asterland, and M. Kellerman, *Modular data logger system for physical workload measurements.* Ergonomics, 2003. **46**(4): p. 407-15.
81. Korshoj, M., J.H. Skotte, C.S. Christiansen, P. Mortensen, J. Kristiansen, C. Hanisch, J. Ingebrigtsen, and A. Holtermann, *Validity of the Acti4 software using ActiGraph GT3X+accelerometer for recording of arm and upper body inclination in simulated work tasks.* Ergonomics, 2014. **57**(2): p. 247-53.
82. Skotte, J., M. Korshøj, J. Kristiansen, C. Hanisch, and A. Holtermann, *Detection of physical activity types using triaxial accelerometers.* J Phys Act Health, 2014. **11**(1): p. 76-84.
83. Cutti, A.G., A. Giovanardi, L. Rocchi, A. Davalli, and R. Sacchetti, *Ambulatory measurement of shoulder and elbow kinematics through inertial and magnetic sensors.* Med Biol Eng Comput, 2008. **46**(2): p. 169-78.
84. Yang, L., W.J.A. Grooten, and M. Forsman, *An iPhone application for upper arm posture and movement measurements.* Appl Ergon, 2017. **65**: p. 492-500.
85. Yu, D., C. Dural, M.M. Morrow, L. Yang, J.W. Collins, S. Hallbeck, M. Kjellman, and M. Forsman, *Intraoperative workload in robotic surgery assessed by wearable motion tracking sensors and questionnaires.* Surg Endosc, 2017. **31**(2): p. 877-886.
86. Wahlström, J., E. Bergsten, C. Trask, S.E. Mathiassen, J. Jackson, and M. Forsman, *Full-shift trunk and upper arm postures and movements among aircraft baggage handlers.* Ann Occup Hyg, 2016. **60**(8): p. 977-90.
87. Bernmark, E. and C. Wiktorin, *A triaxial accelerometer for measuring arm movements.* Appl Ergon, 2002. **33**(6): p. 541-7.
88. Chen, H., M.C. Schall, Jr., and N. Fethke, *Accuracy of angular displacements and velocities from inertial-based inclinometers.* Appl Ergon, 2018. **67**: p. 151-161.
89. Hoehne-Hückstädt, U., C. Herda, R. Ellegast, I. Hermanns, R. Hamburger, and D. Ditchen, *Muskel-Skelett-Erkrankungen der oberen Extremität (BGIA-Report 2/2007). Entwicklung eines Systems zur Erfassung und arbeitswissenschaftlichen Bewertung von komplexen Bewegungen der oberen Extremität bei beruflichen Tätigkeiten (BGIA-Report 2/2007)*. 2007, Hauptverband der gewerblichen Berufsgenossenschaften (HVBG): Sankt Augustin.
90. Ellegast, R., I. Hermanns, and C. Schiefer. *Workload Assessment in Field Using the Ambulatory CUELA System*. 2009. Berlin, Heidelberg: Springer Berlin Heidelberg.
91. Burford, E.M., R. Ellegast, B. Weber, M. Brehmen, D. Groneberg, A. Sinn-Behrendt, and R. Bruder, *The comparative analysis of postural and biomechanical parameters of preschool teachers pre- and post-intervention within the ErgoKiTa study.* Ergonomics, 2017. **60**(12): p. 1718-1729.
92. Lind, C. and M. Forsman, *Accuracy of a posture measurement system for practitioners*. 2015.

93. Schall, M.C., Jr., N.B. Fethke, H. Chen, S. Oyama, and D.I. Douphrate, *Accuracy and repeatability of an inertial measurement unit system for field-based occupational studies.* Ergonomics, 2016. **59**(4): p. 591-602.
94. Morrow, M.M.B., B. Lowndes, E. Fortune, K.R. Kaufman, and M.S. Hallbeck, *Validation of inertial measurement units for upper body kinematics.* J Appl Biomech, 2017. **33**(3): p. 227-232.
95. Schiefer, C., R.P. Ellegast, I. Hermanns, T. Kraus, E. Ochsmann, C. Larue, and A. Plamondon, *Optimization of inertial sensor-based motion capturing for magnetically distorted field applications.* J Biomech Eng, 2014. **136**(12): p. 121008.
96. Mathiassen, S.E., *Diversity and variation in biomechanical exposure: what is it, and why would we like to know?* Appl Ergon, 2006. **37**(4): p. 419-27.
97. Cochran, W.G., *Sampling Techniques*. 1977, Hoboken, NJ: John Wiley & Sons.
98. Liv, P., S.E. Mathiassen, and S.W. Svendsen, *Theoretical and empirical efficiency of sampling strategies for estimating upper arm elevation.* Ann Occup Hyg, 2011. **55**(4): p. 436-49.
99. Mathiassen, S.E., A. Burdorf, and A.J. van der Beek, *Statistical power and measurement allocation in ergonomic intervention studies assessing upper trapezius EMG amplitude. A case study of assembly work.* J Electromyogr Kinesiol, 2002. **12**(1): p. 45-57.
100. Paquet, V., L. Punnett, S. Woskie, and B. Buchholz, *Reliable exposure assessment strategies for physical ergonomics stressors in construction and other non-routinized work.* Ergonomics, 2005. **48**(9): p. 1200-19.
101. Jackson, J.A., S.E. Mathiassen, and P. Liv, *Observer performance in estimating upper arm elevation angles under ideal viewing conditions when assisted by posture matching software.* Appl Ergon, 2016. **55**: p. 208-215.
102. Dartt, A., J. Rosecrance, F. Gerr, P. Chen, D. Anton, and L. Merlino, *Reliability of assessing upper limb postures among workers performing manufacturing tasks.* Appl Ergon, 2009. **40**(3): p. 371-8.
103. Denis, D., M. Lortie, and M. Rossignol, *Observation procedures characterizing occupational physical activities: critical review.* Int J Occup Saf Ergon, 2000. **6**(4): p. 463-91.
104. Stoppa, M. and A. Chiolerio, *Wearable electronics and smart textiles: a critical review.* Sensors (Basel), 2014. **14**(7): p. 11957-92.
105. Searle, S.R., G. Casella, and C.E. McCulloch, *Variance components*. 2006, Hoboken, NJ: Wiley-Blackwell.
106. Liv, P., S.E. Mathiassen, and S.W. Svendsen, *Accuracy and precision of variance components in occupational posture recordings: a simulation study of different data collection strategies.* BMC Med Res Methodol, 2012. **12**: p. 58.
107. Mathiassen, S.E., T. Moller, and M. Forsman, *Variability in mechanical exposure within and between individuals performing a highly constrained industrial work task.* Ergonomics, 2003. **46**(8): p. 800-24.
108. Svendsen, S.W., S.E. Mathiassen, and J.P. Bonde, *Task based exposure assessment in ergonomic epidemiology: a study of upper arm elevation in the jobs of machinists, car mechanics, and house painters.* Occup Environ Med, 2005. **62**(1): p. 18-27.
109. Samuels, S.J., G.K. Lemasters, and A. Carson, *Statistical methods for describing occupational exposure measurements.* Am Ind Hyg Assoc J, 1985. **46**(8): p. 427-33.
110. Allread, W.G., W.S. Marras, and D.L. Burr, *Measuring trunk motions in industry: variability due to task factors, individual differences, and the amount of data collected.* Ergonomics, 2000. **43**(6): p. 691-701.
111. Jackson, J.A., S.E. Mathiassen, and P.G. Dempsey, *Methodological variance associated with normalization of occupational upper trapezius EMG using sub-maximal reference contractions.* J Electromyogr Kinesiol, 2009. **19**(3): p. 416-27.
112. Burdorf, A. and M. van Riel, *Design of strategies to assess lumbar posture during work.* International Journal of Industrial Ergonomics, 1996. **18**(4): p. 239-249.

113. Fethke, N.B., D. Anton, J.E. Cavanaugh, F. Gerr, and T.M. Cook, *Bootstrap exploration of the duration of surface electromyography sampling in relation to the precision of exposure estimation.* Scand J Work Environ Health, 2007. **33**(5): p. 358-67.
114. Hoozemans, M.J., A. Burdorf, A.J. van der Beek, M.H. Frings-Dresen, and S.E. Mathiassen, *Group-based measurement strategies in exposure assessment explored by bootstrapping.* Scand J Work Environ Health, 2001. **27**(2): p. 125-32.
115. Mathiassen, S.E. and V. Paquet, *The ability of limited exposure sampling to detect effects of interventions that reduce the occurrence of pronounced trunk inclination.* Appl Ergon, 2010. **41**(2): p. 295-304.
116. Mathiassen, S.E., J. Wahlström, and M. Forsman, *Bias and imprecision in posture percentile variables estimated from short exposure samples.* BMC Med Res Methodol, 2012. **12**: p. 36.
117. Aitchison, J., *The statistical analysis of compositional data*. 2003, London: Blacburn Press.
118. Mathiassen, S.E. and D. Srinivasan, *Sample size and statistical performance in studies of sedentary behaviour – a novel approach based on compositional data analysis*, in *Proceedings of the IXth international conference "Prevention of Musculoskeletal Disorders"*. 2016: Toronto. p. 74.
119. Reimann, C., P. Filzmoser, K. Fabian, K. Hron, M. Birke, A. Demetriades, E. Dinelli, A. Ladenberger, and G.P. Team, *The concept of compositional data analysis in practice--total major element concentrations in agricultural and grazing land soils of Europe.* Sci Total Environ, 2012. **426**: p. 196-210.
120. Filzmoser, P., K. Hron, and C. Reimann, *Univariate statistical analysis of environmental (compositional) data: problems and possibilities.* Sci Total Environ, 2009. **407**(23): p. 6100-8.
121. Filzmoser, P., K. Hron, and C. Reimann, *The bivariate statistical analysis of environmental (compositional) data.* Sci Total Environ, 2010. **408**(19): p. 4230-8.
122. Chastin, S.F., J. Palarea-Albaladejo, M.L. Dontje, and D.A. Skelton, *Combined Effects of Time Spent in Physical Activity, Sedentary Behaviors and Sleep on Obesity and Cardio-Metabolic Health Markers: A Novel Compositional Data Analysis Approach.* PLoS One, 2015. **10**(10): p. e0139984.
123. Dumuid, D., T.E. Stanford, J.A. Martin-Fernandez, Z. Pedisic, C.A. Maher, L.K. Lewis, K. Hron, P.T. Katzmarzyk, J.P. Chaput, M. Fogelholm, G. Hu, E.V. Lambert, J. Maia, O.L. Sarmiento, M. Standage, T.V. Barreira, S.T. Broyles, C. Tudor-Locke, M.S. Tremblay, and T. Olds, *Compositional data analysis for physical activity, sedentary time and sleep research.* Stat Methods Med Res, 2017: p. 962280217710835.
124. Mathiassen, S.E., J.A. Jackson, and L. Punnett, *Statistical performance of observational work sampling for assessment of categorical exposure variables: a simulation approach illustrated using PATH data.* Ann Occup Hyg, 2014. **58**(3): p. 294-316.
125. Mathiassen, S.E., A. Burdorf, A.J. van der Beek, and G.A. Hansson, *Efficient one-day sampling of mechanical job exposure data--a study based on upper trapezius activity in cleaners and office workers.* AIHA J (Fairfax, Va), 2003. **64**(2): p. 196-211.
126. Mathiassen, S.E., P. Liv, and J. Wahlström, *Cost-efficient measurement strategies for posture observations based on video recordings.* Appl Ergon, 2013. **44**(4): p. 609-17.
127. Rezagholi, M. and S.E. Mathiassen, *Cost-efficient design of occupational exposure assessment strategies--a review.* Ann Occup Hyg, 2010. **54**(8): p. 858-68.
128. Mathiassen, S.E. and K. Bolin, *Optimizing cost-efficiency in mean exposure assessment--cost functions reconsidered.* BMC Med Res Methodol, 2011. **11**: p. 76.
129. Heiden, M., J. Garza, C. Trask, and S.E. Mathiassen, *Predicting Directly Measured Trunk and Upper Arm Postures in Paper Mill Work From Administrative Data, Workers' Ratings and Posture Observations.* Annals of Work Exposures and Health, 2017. **61**(2): p. 207-217.
130. Burdorf, A., *Bias in risk estimates from variability of exposure to postural load on the back in occupational groups.* Scand J Work Environ Health, 1993. **19**(1): p. 50-4.

131. Tielemans, E., L.L. Kupper, H. Kromhout, D. Heederik, and R. Houba, *Individual-based and group-based occupational exposure assessment: some equations to evaluate different strategies.* Ann Occup Hyg, 1998. **42**(2): p. 115-9.
132. Nordander, C., I. Balogh, S.E. Mathiassen, K. Ohlsson, J. Unge, S. Skerfving, and G.Å. Hansson, *Precision of measurements of physical workload during standardised manual handling. Part I: surface electromyography of m. trapezius, m. infraspinatus and the forearm extensors.* J Electromyogr Kinesiol, 2004. **14**(4): p. 443-54.
133. Armstrong, T.J., A. Burdorf, A. Descatha, A. Farioli, M. Graf, S. Horie, W.S. Marras, J.R. Potvin, D. Rempel, G. Spatari, E.P. Takala, J. Verbeek, and F.S. Violante, *Scientific basis of ISO standards on biomechanical risk factors.* Scand J Work Environ Health, 2018. **44**(3): p. 323-329.
134. *ISO 11226. Ergonomics - Evaluation of static working postures*, in *ISO*.
135. *DIN EN 1005-4:2009-01. Safety of machinery - Human physical performance - Part 4: Evaluation of working postures and movements in relation to machinery*.
136. *ISO 11228-3. Ergonomics - Manual handling - Part3: Handling of low loads at high frequency*, in *ISO*.
137. Coenen, P., M. Douwes, S. van den Heuvel, and T. Bosch, *Towards exposure limits for working postures and musculoskeletal symptoms - a prospective cohort study.* Ergonomics, 2016. **59**(9): p. 1182-92.
138. Jonker, D., E. Gustafsson, B. Rolander, I. Arvidsson, and C. Nordander, *Health surveillance under adverse ergonomics conditions--validity of a screening method adapted for the occupational health service.* Ergonomics, 2015. **58**(9): p. 1519-28.
139. Nordander, C., K. Ohlsson, I. Åkesson, I. Arvidsson, I. Balogh, G.Å. Hansson, U. Strömberg, R. Rittner, and S. Skerfving, *Exposure-response relationships in work-related musculoskeletal disorders in elbows and hands - A synthesis of group-level data on exposure and response obtained using uniform methods of data collection.* Appl Ergon, 2013. **44**(2): p. 241-53.
140. Arvidsson, I., C. Dahlqvist, H. Enquist, and C. Nordander, *Åtgärdsnivåer mot belastningsskada. Arbets- och miljömedicin Syds rapport nr.18/2017*. 2017, Arbets- och miljömedicin Syd.

12 Appendix

12.1 Appendix A: Possible variables for analysis of arm elevation data measured by technical means

The following section offers a list of variables that can be derived from a time-line of arm elevation and are recommended for analysis. See Chapter 6.3 for guidance.

Postures:
10th, 50th, 90th, 99th percentiles of arm elevation (°)
Duration (minutes and % of working time) above elevation levels: 10°, 20°, 30°, 45°, 60°, 90°, 120°
Duration (% of working time) and frequency (number per hour) of uninterrupted periods with:

- Elevation >20° for >5, > 10, >20, >30, >60, >120 seconds
- Elevation >60° for >5, > 10, >20, >30, >60 seconds
- Elevation >90° for >5, > 10, >20, >30 seconds
- Elevation <20° for >3 seconds

Movement velocities:
10th, 50th, 90th, 99th percentiles of arm elevation velocity (°/s)
Duration (% working time) of uninterrupted periods >3s with velocity <5°/s
Duration (% working time) of periods with velocity >90°/s

Posture and movement:
Duration (% working time) of periods at “rest” (elevation <20° and velocity <5°/s)

12.2 Appendix B: Analyses and outcome variables for comparison with ISO guidelines

Guidelines for upper arm elevation exist in the form of ISO 11226 and ISO 11228-3. These guidelines were set with observational methods in mind for data acquisition. In these guidelines, a distinction is drawn between static and dynamic (repetitive) postures/movements. No definitive definition exists of static or dynamic; interpretation of what constitutes a functional movement or a static posture is left to some extent to the observer.

Conversion of continuous angle series into parameters which can be compared with guidelines necessitates: (1) an algorithm that calculates these outcome parameters; (2) more detailed definitions of static and dynamic postures/movements.

In this patent, we propose an algorithm for posture evaluation: EP2508127A1 Method and system for posture evaluation. van Rhijn, R.G.J.W.; Bosch, T.; Könemann, R. (http://www.google.sr/patents/EP2508127A1?cl=nl)

A short summary of the analysis steps of this algorithm:

1. Simplify angle signal to subsequent peaks and local minima
2. Filter out the relevant peaks and local minima of functional movements (static and dynamic)
   I. Dynamic postures: an upper arm movement visible (to the eye) with a certain amplitude from a local minimum to peak angle to a local minimum, peak above a threshold angle, without a holding time longer than x seconds at the peak angle.
   II. Static postures: an upper arm is raised to a certain peak angle and maintained raised around this peak angle for a certain time. Minor movements of the arm will not terminate the static posture.
3. Calculate outcome parameters for dynamic and static postures.

Calculations and outcome parameters

Dynamic posture: An upper arm is raised above a certain threshold Ao to a final peak angle and lowered within T1 by at least A1 degrees. The next movement starts at the following local minimum. A final peak (+) is a peak which is followed by a local minimum, at least A1 degrees lower. Reverse for a final local minimum(*)

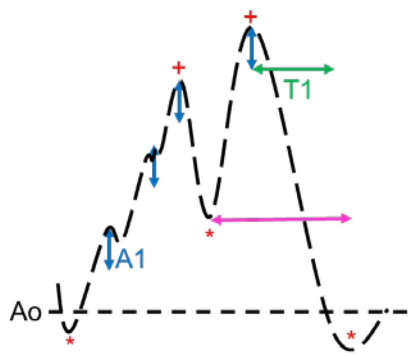

Figure B.1: Simplified example of calculation of dynamic postures

Parameters of a dynamic posture:

- Height of final peak angle (°)
- Duration of movement from subsequent final local minima (pink arrow)
- Frequency of movements, number of final peaks per time unit
    - o Option to split frequency in angle ranges (i.e. 20-60° and >60°)

Static posture: Subsequent peaks and local minima above a certain threshold (Ao) within an angle range of +/- A1 compared to the first of the subsequent peaks, adopted for more than T1 seconds measured from the first to the last peak within the angle range.

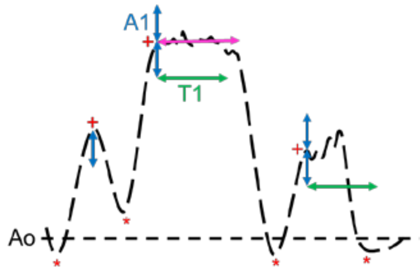

Figure B.2: Simplified example of calculation of static postures

Parameters of a static posture:

- Average angle (°) of peaks and local minima within the angle range
- Duration of static posture from the first to the last peak within the angle range (pink arrow)
- Static postures in % of total time
    - o Option to split % in angle ranges (i.e. 20-60° and >60°)