Human-Centred Automation to Simplify the Path to Social and Economic Sustainability

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Abstract Musculoskeletal Disorders (MSDs) pose a serious threat to sustainability in manufacturing. In particular, this phenomenon impacts the sustainability indicators of worker health and safety and the Gross Domestic Product (GDP). Effective MSD prevention measures would therefore constitute a remarkable contribution to social and economic sustainability. This chapter provides first an outline of existing methods to prevent MSD at the workplace. Analysis of the approaches yields that effective solutions require earmarked finances as well as qualified personnel, both of which are not affordable for many companies. In pursuit of solutions, Human-centred Automation (HCA), a recent paradigm in manufacturing, proposes the design of manufacturing systems using intelligent technology to support the worker instead of replacing him/her. HCA has the unique potential of reducing the effort needed to implement MSD prevention strategies by simplifying the path to social and economic sustainability. This chapter demonstrates this process with the example of the "Working Posture Controller" (WPC), which illustrates how the HCA concept can be applied. Finally, the lessons learned from the case are outlined, providing a vision of how future workplaces can benefit from HCA.

Keywords Musculoskeletal disorders · Human-centred automation · Human-machine interaction

1 Work-Related Musculoskeletal Disorders—A Sustainability Challenge

The health of the workforce is vital for social as well as economic sustainability. The Guideline for Social Life Cycle Assessment of Products (Benoît et al. 2010) describes "worker health and safety" as a major impact category among social

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sustainability indicators. In terms of economic sustainability, direct costs due to unfavourable working conditions reduce a country's Gross Domestic Product (GDP) (Bevan 2015), which is considered to be one of the main economic sustainability indicators defined by the United Nations—Department of Economic and Social Affairs (2007).

Musculoskeletal Disorders (MSDs) present a serious threat to the health of the workforce, and thus, to sustainability. The European Agency for Safety and Health at Work (Schneider et al. 2010) defines MSDs as "health problems of the locomotor apparatus, which includes muscles, tendons, the skeleton, cartilage, the vascular system, ligaments and nerves." Work-related or Occupational Musculoskeletal Disorders (WMSDs) encompass all MSDs that are caused or worsened by work.

WMSDs as a sustainability indicator are not explicitly mentioned in the "health and safety" impact group in Benoît et al. (2010). However, this represents more of an oversimplification of the guideline than a negligible effect. In fact, the only measures which are considered are those which result from suboptimal working conditions, such as the number of injuries or accidents (Chang et al. 2016). Accumulative effects, such as WMSDs go completely neglected although they pose a comparable impact. The European Labour Force Survey (Camarota 2007) concluded that MSDs accounted for 53 % of all work-related diseases in the EU-15, therein representing the most frequent cause (Bevan 2015). The number of lost days due to WMSDs is estimated at 350 million (Delleman et al. 2004) in the EU. In terms of economic sustainability, WMSDs significantly reduce the GDP of the EU. The total costs of WMSDs is estimated at 240€ billion, which translates into up to 2 % of the EU GDP (Bevan 2015).

Due to its impact, researchers from different scientific disciplines, such as human factors science, medicine and engineering, have developed methods to prevent WMSDs, reducing their risk of occurrence. Significant successes have been achieved. On average, methods implemented have turned out to cover their total costs in less than 1 year (Goggins et al. 2008). Nevertheless, implementing effective measures requires tedious work on the part of highly qualified ergonomists, which makes effective WMSD prevention not realisable for every company.

Human Centred Automation (HCA) denotes a recent development in manufacturing technology. This engineering paradigm proposes turning away from fully automated production lines in favour of systems where man and machine collaborate and combine the strengths of both participants. Instead of replacing the worker, the machine's task is to support him/her. The system can enhance cognitive skills through intelligent sensors or provide additional physical capabilities through actuators. By automatising the parts of the WMSD prevention methods which require highly skilled personnel or tedious work, HCA helps to make these techniques available to a broader mass. To sum up, the contribution of HCA to sustainability lies in providing access to sustainability enhancing techniques.

This chapter concentrates on one main risk factor causing WMSDs: unfavourable working posture, which is often referred to in literature as "awkward posture" (Delleman et al. 2004). An exemplary technique is presented on how HCA can be applied to solve existing WMSD prevention problems, and thus, support sustainability goals in manufacturing. Section 2 provides an overview of common state-of-the-art approaches in tackling WMSDs, outlining a fundamental problem: the effectiveness–flexibility trade-off. The HCA, which appears to be a promising solution to the effectiveness–flexibility trade-off, is presented in Sect. 3. Afterwards, Sect. 4 presents the Working Posture Controller (WPC). The WPC is a device which demonstrates how the HCA paradigm is used to overcome the effectiveness–flexibility trade-off. Finally, this chapter concludes with the facts learned.

2 State-of-the-Art of WMSD Prevention

Due to its high impact on human health and the economy, the area of WMSD prevention is an extensive research field. Researchers from various disciplines such as, human factors, medicine or engineering, have proposed their solutions. In scientific literature, the measures are often referred to as "ergonomic interventions." This section outlines the most important developments.

In brief, the techniques presented can be grouped into three categories: technical measures, organisational measures or individual measures (Van der Molen et al. 2005). Alternatively, Bergamasco et al. (1998) use the term "training" instead of individual measure.

Technical measures involve modifications of the working environment and the process. Examples include designing the workplace layout, process design, or the introduction of special equipment to support the worker. Workplace layout design aims at rearranging the workplace geometry in such a way that tasks can be efficiently accomplished without the need for adopting awkward postures. To that effect, ergonomic guidelines have been released to provide the workplace designer with a tool for checking the appropriateness of the developed workplace (Das and Grady 1983). The set of ergonomic guidelines is complex and highly dependent on the tasks at hand and on the individual person. Often, multiple physical prototypes have to be evaluated (Delleman et al. 2004). Digital Human Models (DHM) have become a popular method for assisting in the design process (Lämkull et al. 2009) by means of simulating the prototypes. Technical measures also imply the introduction of equipment, such as lifting aids or human robot collaboration systems to execute physically demanding tasks on behalf of the worker (Krüger et al. 2009; Busch et al. 2012; Weidner et al. 2013; Schmidtler et al. 2014). Another type of equipment is found in alert systems which monitor the process and warn the user as soon as an ergonomically unfavourable situation arises (Vignais et al. 2013).

In addition, organisational measures (Paul et al. 1999) entail techniques which aim at avoiding an inacceptable amount of load through customised and calculated, balanced scheduling of the tasks. The idea is to compose the set of tasks for a worker in a way such that multiple regions of the body are alternatingly strained. This avoids the monotonous strain of one particular body structure leading to long-term damage. This technique is called job rotation.

Finally, individual measures (Engels et al. 1998) supply the worker with basic knowledge about best practices so as to enable the preservation of one's own health. This can include biomechanical theory, general ergonomics, or techniques e.g. for lifting. Often, the theoretical courses are complemented with practical training.

Multiple approaches are available for tackling the WMSD dilemma. A decision-maker has the challenge of selecting the most promising approaches to be implemented. To that end, Goggins et al. (2008) have proposed a scale for ranking the measures according to their effectiveness (see Fig. 1). The scale is based on a Cost-Benefit analysis derived from the review of around 250 studies in industrial as well as office environment. This scale comprises four classes:

- measures that completely eliminate the exposure (level 1)
- measures that reduce the level of exposure (level 2)
- methods that reduce the exposure time (level 3)
- and methods, whose success merely rely on the worker's behaviour (level 4).

Level 1 methods are the most effective ones whereas level 4 methods should only be considered if the other measures are infeasible.

Apart from their effectiveness, the specific amount of effort required to implement the measures has to be considered. The techniques can be grouped into two categories: pre-process techniques and in-process techniques. Pre-process techniques require the effort attached to tailoring the method to the individual task and user groups at hand. In changing the production environment requiring flexible production systems, these measures can produce a bottleneck. Examples are workplace design or organizational measures. In-process measures, on the other hand, only require one initial setup routine and then adapt to changing situations. Examples are found in so-called *cobots* or alert systems. Their impact is however limited, since their adaptation normally only covers few well-defined cases. In conclusion, a fundamental trade-off exists between the effectiveness and the flexibility of the ergonomic intervention techniques.

Though entailing tremendous effort, Goggins et al. (2008) state that the impact of the interventions measured has been highly promising. Incidence rates have, for example, dropped by 65 % on average and companies had to pay 68 % of the original compensation costs after intervention. Additionally, the productivity of the workforce and the quality of the products have improved. Most notably, these

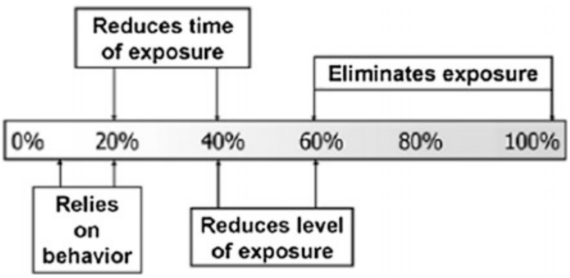

Fig. 1 Scale of effectiveness according to Goggins et al. (2008)

effects appear within less than 1 year after implementation. The challenge lies in addressing how to achieve a high effect without losing out on flexibility.

3 The Potential of Human-Centred Automation (HCA) for Sustainability

With the introduction of computers, manufacturing has been veritably revolutionised. Tasks which had been time-consuming and tedious can now be efficiently performed with relative ease. At the same time, tasks which originally required human experts have been simplified in such a way that lower skilled operators can use them.

In recent years, techniques of Human-centred Automation (HCA) have become a matter of research. The original term comes from the domain of aviation and was introduced by Bilings (1997). HCA describes a novel approach in system design. It proposes building an environment, "in which humans and machines collaborate cooperatively in order to reach stated objectives." This paradigm has been applied in various systems, such as driver assistance systems, aircraft flight management systems and air traffic systems.

Furthermore, HCA has increasingly become a matter of research in manufacturing. In this domain, HCA represents a new paradigm of turning away from full automatisation as a long-term goal, and instead moves in the direction of achieving more flexible manufacturing structures. Systems of HCA strive to support the worker rather than to replace him/her with technology. The human remains the core of the process and the technology is used to enhance cognitive skills by sensors and physical skills by actuators. The result is a production system wherein worker and machine are tightly bound together, combining one other's strengths and compensating for each other's weakness.

To be sure, both human and automation systems have their advantages and shortcomings. Humans are highly flexible insofar as being able to learn new tasks in a short time. Yet, the human is vulnerable. Automation technology with its actuators proves however to be quite powerful and can efficiently accomplish repetitive tasks. On the other hand, flexibility is lost in that process, since programming the machines likewise takes time and is work intensive, making it only suitable in high lot size production scenarios.

Recent developments in the field of intelligent systems have made it possible to develop systems which support the human in a more sophisticated manner. The trouble with the solutions mentioned in Sect. 2 is that they require human expertise. Considering the lack of experts to implement the solutions, the only way to escape this dilemma is to teach machines to take over some of the tedious as well as sophisticated manual tasks. In this way, HCA can help to implement measures designed to reduce health risks at the workplace with an acceptable level of effort.

4 The Working Posture Controller (WPC)

WMSDs present a grave problem for the manufacturing community. Especially considering the ageing worker population in many countries, these disorders are poised to become a significant sustainability challenge. Remarkable effort has been put into solving the WMSD issue. Yet, a fundamental trade-off in the solutions proposed stands at the crossroads: either the measures are effective but inflexible, or they are easily adaptable but less effective. Nevertheless, some experts have concluded that HCA techniques are starting to make an impact on manufacturing by combining the best of both worlds. A particular motivation for HCA has been the need for flexibility without the need to relinquish the advantages bestowed by automation technology.

All these facts taken together indicate that the solution to the problem seems to lie in applying HCA techniques to confront the WMSD challenge. The questions to be posed are: What exactly do the resulting systems look like? How can such systems be technically realised? This section attempts to provide answers by presenting an exemplary device: the Working Posture Controller (WPC) (Krüger and Nguyen 2015; Nguyen et al. 2016).

The WPC is a system that continuously monitors the worker's posture in the process and adjusts the workplace layout when the combination of task and workplace does not allow for a natural working posture. Through automatising the work and knowledge-intensive parts in the highly effective measures, flexibility is gained.

4.1 Concept of the WPC

The main conceptual idea of the WPC is to combine automatised ergonomic assessments with automatised workplace design into one system. This system enables the user to avoid adopting awkward posture for prolonged periods. In the workflow, man and machine are embedded into a control loop. Figure 2 depicts one full sequence. A posture assessment module monitors the worker's posture, assigning a numerical score which represents the current postural load of the task. If the score exceeds a particular value, the system initiates the posture optimisation module. This component first interprets the worker's posture to interpret which task he/she intends to accomplish. Afterwards, it computes a workplace layout adjustment which enables accomplishing the same task with a more ergonomic posture. Having found this adjustment, the system then gives feedback to the user, providing a visual of the proposed workplace geometry and posture. Once the worker agrees, the adjustment is executed. Upon adjustment, the cycle then starts anew. The coming subsections describe the two components in further detail.

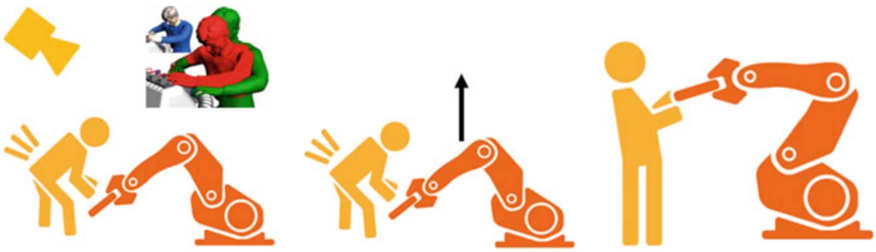

Fig. 2 Concept of the WPC. An actuator, in this case a robot, holds the workpiece to be processed. Additionally, a sensor system monitors the worker's posture. In case the posture becomes physically straining, the WPC proposes the change to the workpiece pose, making it possible for the user to adopt a more natural posture

4.2 Posture Assessment

The posture assessment module is based on the "Ergonomic Assessment Worksheet (EAWS)" (Schaub et al. 2013), a manual tool to help ergonomic practitioners assessing working tasks. The whole concept behind it is that the practitioner observes the task and assigns load points for the duration of the particular working postures adopted. The EAWS defines a set of postures which have to be recognised from observation. The accumulated score of the single posture durations yields the overall postural risk score.

Automatising this posture assessment process requires the system to automatically recognise the right posture from the defined one. The WPC uses a consumer depth camera to acquire the input data. Afterwards, a markerless motion capture algorithm (Nguyen et al. 2014) is developed to determine the coordinates of each limb. Having obtained the coordinates, classifiers are trained on training datasets to recognise the posture. Upon recognition, load points can be assigned and the current risk score can be accumulated accordingly. If this ergonomic score exceeds a given threshold, an adjustment is then initiated.

4.3 Posture Optimisation

Having detected the ergonomically critical situation, the posture optimisation algorithm attempts to compute an alternative workplace adjustment where the worker is able to accomplish the same task in a healthier posture.

The algorithm first interprets the original task intended from the recognised posture. Relevant parameters to be detected lie in the orientation of the upper arm and the location of the hands relative to the workpiece. Afterwards, the algorithm searches for an adjustment of the workplace geometry, which enables accomplishing the task in an ergonomically more favourable posture. The biggest challenge lies in mathematically modelling the human behaviour at hand. The posture

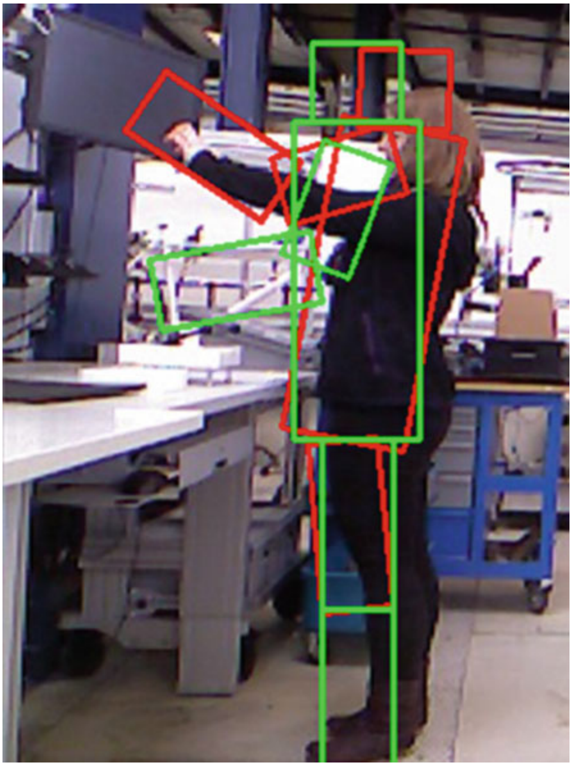

Fig. 3 The *red manikin* denotes the current posture whereas the *green manikin* denotes the optimised working posture after adjustment

adopted once a potential adjustment has been taken, then has to be predicted. The behaviour is modelled by transforming the task into non-linear mathematical optimisation problem which can be solved with standard optimisation algorithms. Different types of actuators yield different optimisation problems. An exemplary visualisation of original and predicted posture after adjustment is depicted in Fig. 3.

5 Discussion and Outlook

WMSDs have a high negative impact on social as well as economic sustainability. The WPC shows that HCA can be successfully applied to improve WMSD prevention methods. This novel way of preventing awkward posture combines sensors, intelligent algorithms and actuators to enable the machine to perform tasks which would normally require human expertise in less time. Through the time-intensive and tedious process of setting up the parts of the workplace design to fit the automation technology, the whole production system gains the flexibility required. The system is designed to be usable with cost-efficient as well as advanced hardware in order to address a broad group of users.

Implementing HCA concepts into further manufacturing requires a discussion of the fundamental problems of man-machine interaction. First of all, engineers have to define the appropriate level of automation (LoA) for the given system. The term LoA is defined by Frohm (2008) as "allocation of physical and cognitive tasks between humans and technology, described as a continuum ranging from totally manual to total automation." The problem is summed up by the question: what is supposed to be done by the human and what is supposed to be done by technology? The answer to this question will influence what such systems look like, and in what manner they assist the worker. Second, after defining how to allocate the task, designers have to define how human and technology are supposed to communicate. This aspect is critical for the acceptance of HCA. Common mistakes in the design of communication between human and machine are described in such works as Endsley's (1995).

To conclude, HCA stands as a promising means of supporting social and economic sustainability goals. However, designing these systems is challenging, since it is not known exactly what form they ultimately take. The WPC, among other projects, has shown one example of how such a system can be designed.

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