Sensors@Work

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Chapter 1

General introduction

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1.1 | Sustainable workforce

Worldwide, life-expectancy is rapidly increasing and the population is aging (Gotmark, et al., 2018; Rechel, et al., 2013; Huang, 2018; Ota, et al., 2018; Lyons, et al., 2018). By 2025, it is predicted that more than 20% of European society will be older than 65 years and this figure will double by 2060 (Gotmark, et al., 2018; Koolhaas, et al., 2009; Stoeldraijer, et al., 2017). An effect of an aging population is a lower number of younger citizens and workers (between 18 and 45 years) and an increase in older citizens and workers (≥45 years (Koolhaas, et al., 2009; Hupkens, 2006; Kenny, et al., 2008)) resulting in an aging workforce (Rechel, et al., 2013; Huang, 2018; Lyons, et al., 2018; Koolhaas, et al., 2009). Biological aging comes with physical changes (Adams & White, 2004) associated with a decrease of muscle mass and lower energy levels (Koolhaas, et al., 2009; Brouwer, et al., 2013; Shephard, 1997; Ilmarinen, 2001). Next to biological aging, the presence of chronic diseases plays an important role (Koolhaas, et al., 2009; Weerding, et al., 2005). In the Netherlands, 40% of older workers have one or multiple chronic diseases, which cause 54% of them to have problems performing their daily job (Koolhaas, et al., 2009; Weerding, et al., 2005; Jorgensen, et al., 2013). This number will increase rapidly with the increase of the average age of workers. This will affect well-being as well as workability, work performance, quality, and safety (Koolhaas, et al., 2009; Brouwer, et al., 2013; Varianou-Mikellidou, et al., 2019; Arts & Otten, 2013; Kirkland & Dobbin, 2009). Additionally, it will lead to an increase in absenteeism costs for companies, the government and the (working) population, not only in the Netherlands but across Europe and the Western world (Koolhaas, et al., 2009; Kenny, et al., 2008; Brouwer, et al., 2013; Ilmarinen, 2001; Kirkland & Dobbin, 2009). To redeem the costs of aging and to maintain a stable workforce and economy, multiple countries have increased the retirement age (Rechel, et al., 2013; Brouwer, et al., 2013; Arts & Otten, 2013). This alone, however, will not be enough to maintain a sustainable health care system nor a sustainable and healthy workforce.

To create a sustainable workforce, the balance between work capacity and workload plays an important role (Wu & Wang, 2002). The workability of workers is influenced by multiple factors as shown in Figure 1.1, the expanded model of the World Health Organization (WHO) International Classification of Functioning (ICF). These aspects can be roughly divided into external (physical and mental) factors, personal factors, and health (Heerkens, et al., 2004). The external factors of work determine the workload, whereas personal factors and health determine work capacity.

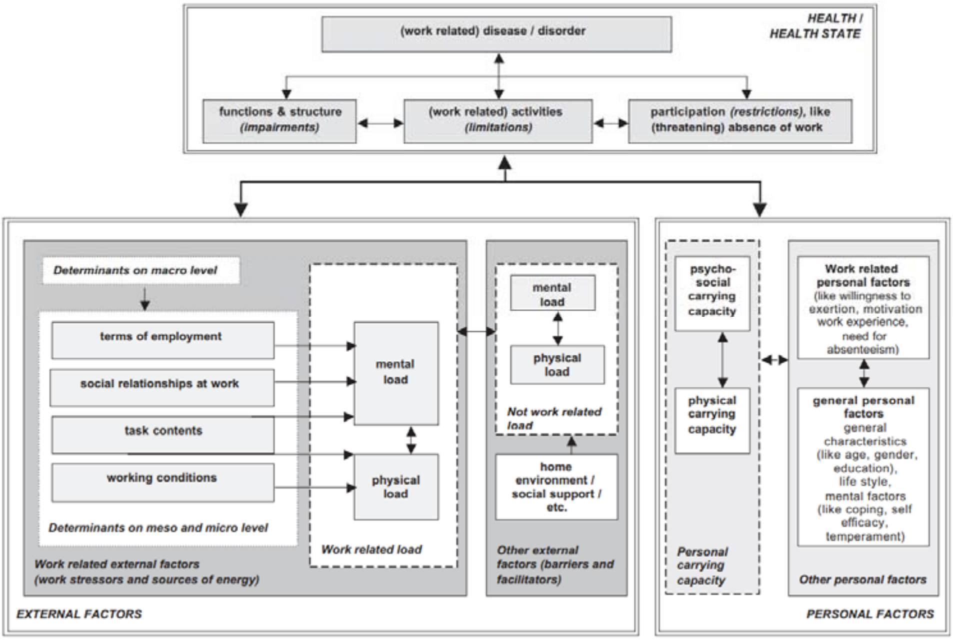

Figure 1.1 | The expanded model of the World Health Organization (WHO) International Classification of Functioning (ICF) by Heerkens (2004); the ICF scheme including mental and physical external factors and personal factors influencing the workability (Heerkens, et al., 2004).

Every worker has an individual workload which depends on the type of work he/she does, the work activity and its intensity (Heerkens, et al., 2004; Karasek & Theorell, 1990; Bakker, 2002; Ng & Feldman, 2013; Costa-Black, et al., 2013). The workload and demand influence the external load, such as work posture, the weight of objects, the duration of the task and the actual working method (Westgaard & Winkel, 1996) (Hoozemans, et al., 1998). These external workloads create an internal load on the body of the worker (Costa-Black, et al., 2013; Hoozemans, et al., 1998; Schultz, et al., 2007). This internal workload causes an acute response within the body with a short and long-term effect on the body, health and work capacity (Schultz, et al., 2007; Westgaard & Winkel, 1996; Hoozemans, et al., 1998; van Dijk, et al., 1990). The individual (work) capacity depends on the health (presence of diseases), age, lifestyle, and physical and cognitive fitness of the worker (Heerkens, et al., 2004; Costa-Black, et al., 2013; Schultz, et al., 2007). In balance, the work capacity exceeds or is the same as the workload. When the work capacity is lower than the workload, there is an imbalance and overload will occur (Kenny, et al., 2008). Due to biological aging and the presence of chronic diseases, work capacity lowers. With an unchanged workload, this can result in an imbalance causing structural overload. Structural overload will result in fatigue, lowered well-being, health problems and finally absenteeism (Kenny, et al., 2008; Ilmarinen, 2001; Weerding, et al., 2005; Costa-Black, et al., 2013). To gain a healthy aging working population, structural overload needs to be prevented (Korshoy, et al., 2013; Wu & Wang, 2002; Karasek & Theorell, 1990; Bakker, 2002).

1.2 | Physical workload

Mainly physically active workers, such as construction workers and firefighters, experience work-related health problems caused by a lower capacity due to aging or presence of chronic diseases (Koolhaas, et al., 2009; Brouwer, et al., 2013; Shephard, 1997; Ilmarinen, 2001) and a high physical workload for the body (Spook, et al., 2019; Andersen, et al., 2016). Physically underloaded workers, such as office workers, also experience discomfort, however, this is caused by high local physical loads on the body caused by inactivity (Netten, et al., 2011; Thorp, et al., 2012; Healy, et al., 2013). Despite the different characters, both forms of physical workload can cause health problems and require attention (Andersen, et al., 2016; Hallman, et al., 2016; Mathiassen, 2006).

This physical workload can be divided into mechanical and energetic loads (Jorgensen, et al., 2013; Kuijer, et al., 1999; van der Molen, et al., 2008). The mechanical workload is the load on the musculoskeletal system (internal load) caused by working posture, load on the muscles, and repetition (external load). This could be a static load, such as working for a prolonged period of time in the same position which is typical for office and assembly line workers, or a dynamic load where the working posture frequently varies as typical for workers in physically demanding occupations (SBCM, 2013). The energetic workload is the amount of energy that the body must expend (internal load) to be able to perform work-related activities (external load) (Bernmark, et al., 2012; Seeherman, et al., 1981; Deerenberg, et al., 1998; Bruce, et al., 1973; Taylor, et al., 1955). It depends on the duration and intensity of these activities and will be affected by influences such as heat exposure and temperature change (external loads) (Bernmark, et al., 2012; Wingo, et al., 2005; Seeherman, et al., 1981; Deerenberg, et al., 1998; Bruce, et al., 1973). As illustrated in the conceptual model of Panel on Musculoskeletal Disorders and the Workplace (2001) (see Figure 1.2) (Schultz, et al., 2007; Panel on Musculoskeletal Disorders et al., 2001), which zooms in on the external and personal factors presented in the expanded model of WHO-ICF (2004) (Figure 1.1), the external workloads of the workplace, as task contents and working conditions, create an internal load on the worker on which the body reacts with a physiological response (Schultz, et al., 2007; Panel on Musculoskeletal Disorders et al., 2001). This can cause a mechanical strain and (physical) fatigue. With an imbalance between workload and capacity, it can cause long-term pain, discomfort, impairment, and disabilities. This misbalance could be prevented by (1) monitoring the individual balance between workload and capacity, and (2) interventions to lower the workload and/or increase work capacity and support to the worker during work.

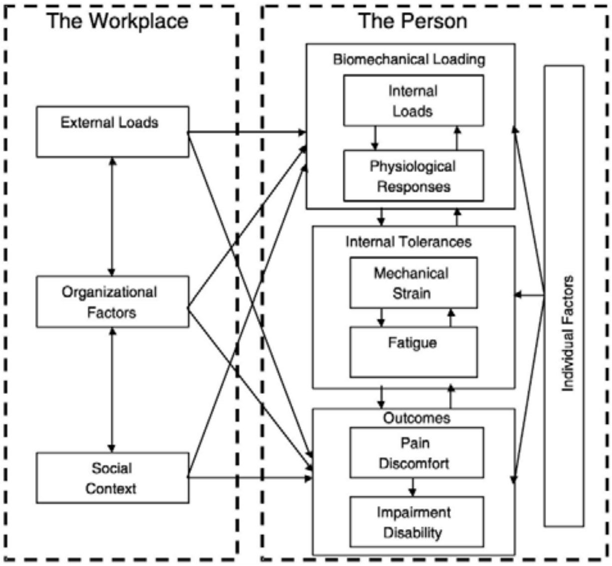

Figure 1.2 | Conceptual model of the roles and influences individual, external and internal factors on (musculoskeletal) workload and health from Panel on Musculoskeletal Disorders and the Workplace, Commission on Behavioural and Social Sciences and Education, National Research Council (NRC) and Institute of Medicine (IOM) (Panel on Musculoskeletal Disorders et al., 2001).

1.3 | Sensor technologies

The main challenge is monitoring the workload and specifically the individual balance between this and work capacity whilst performing the job. Nowadays, the workload is monitored by questionnaires, observations, or in controlled lab situations (Radwin & Lavander, 1999). Self-reporting questionnaires are based on an individual's perception and provide limited information about the actual workload (Cleland, et al., 2014; Harvey, et al., 2013; Clark, et al., 2011). Visual observations by trained specialist are time-consuming, come with high labour costs, are often snapshots of the overall daily working conditions and do not take into account individual aspects such as the presence of diseases or being overweight which affects the internal reaction on external load (Ng & Feldman, 2013; Cavuoto & Nussbaum, 2014; Maman, et al., 2017; Michalos, et al., 2018; Gallagher & Heberger, 2013; Garg & Kappellusch, 2009). The available objective monitoring systems need to be used in controlled lab situations (Maman, et al., 2017; Vandermissen, et al., 2014; Perronia, et al., 2014), interfere with workability or are not validated or reliable (Wu & Wang, 2002; Vandermissen, et al., 2014; Takala, et al., 2010; Kuijper & Frings-Dresen, 2004; Verschoof, et al., 2005; Boa, et al., 2004). There is a lack of objective monitoring instruments and a need for wearable sensor technologies to monitor individual workload during work time (Wu & Wang, 2002; Maman, et al., 2017; Verschoof, et al., 2005; Aryal, et al., 2017; Netten, et al., 2011; Pancardo, et al., 2015; Mazgoaker, et al., 2017; Patel, et al., 2012). Sensor technologies may be useful for objectively monitoring workers' workloads (Zhang, et al., 2017). However, there is a lack of sensor technologies that reliably and validly measure aspects of the workload during work without limiting workability (Maman, et al., 2017; Vandermissen, et al., 2014; Takala, et al., 2010; Kuijper & Frings-Dresen, 2004; Verschoof, et al., 2005; Boa, et al., 2004; Aryal, et al., 2017; Netten, et al., 2011; Wu & Wang, 2002; Pancardo, et al., 2015; Mazgoaker, et al., 2017; Patel, et al., 2012).

In the project SPRINT@Work it has been investigated how sustainable employability can be created and how an aging population can be kept healthy and employable in the long-term. One of the challenges was to avoid a structural overload concerning the physical workload. The aim was to make workers aware of their behaviour by (1) monitoring workload and capacity objectively by developing and testing sensor technologies and telemonitoring, and (2) providing interventions to increase their work capacity or lower the workload.

Figure 1.3 | SPRINT@Work is facing the challenge to make the aging population healthy and deployable.

1.4 | Needs and relevance

For workers and companies, as well as the European population, it is very important to realise a sustainable workforce, and sensor and intervention technologies may contribute to this. Although this will not solve all the problems surrounding realising a sustainable workforce, such as working conditions and safety hazards, it will increase insight regarding internal workload as well as contributing to the workers' awareness about their own working behaviour (Spook, et al., 2019). This should ultimately have a positive effect on the workability, health, well-being, quality, and safety of workers and contribute to the existence of a sustainable workforce. For workers and employers, sensor and intervention technologies are of interest to monitor the workload during work with a wearable and easy-to-use system. By using these, workers can be made aware of their working behaviour and provided with personalized, real-time feedback (Spook, et al., 2019; Zhang, et al., 2017). These technologies must not interfere with workability and must be robust whilst complying with company and workplace regulations (Spook, et al., 2019). Moreover, the system must be safe to use (Santos, et al., 2020), data ownership must be clear, and privacy protected (Spook, et al., 2019). And workers should be able to use outcomes to later open a dialogue about workplace improvements (Spook, et al., 2019).

According to literature research and a needs assessment among companies (employees and employers) in Northern-Netherlands (Spook, et al., 2019), there is a need for sensor technologies to monitor the workload and three physical aspects emerge (Radwin & Lavander, 1999). Firstly, the mechanical load of workers. Musculoskeletal disorders and low back pain (Jorgensen, et al., 2013; Holterman, et al., 2013; Andersen, et al., 2007; Bakker, et al., 2009; Andersson, 1999) are common health problems and a major cause of work absence among office and physically active workers (Coenen, et al., 2016; Jezukaitis & Kapur, 2011; Palmer & Goodson, 2015). This is mainly caused by a prolonged working in same the working posture (static load) or (high external loads while) working in unfavourable postures (Schultz, et al., 2007; Panel on Musculoskeletal Disorders et al., 2001). There is a need, but lack on methods or instruments to monitor the working posture (and related load on the back (internal load)) during the performance of the job (Jorgensen, et al., 2013; Netten, et al., 2011; Takala, et al., 2010; Xu, et al., 2012; Juul-Kristensen, et al., 2001) of individuals (Hansson, et al., 2006). Secondly, the energetic workload and its health consequence fatigue (internal load) (Spook, et al., 2019; Radwin & Lavander, 1999). Due to aging, the energetic capacity declines starting at an age of 30 years (Kenny, et al., 2008; Ilmarinen, 2001; Chan, et al., 2000; Bellew, et al., 2005) and significantly influences the workability of physically active workers. When the workload exceeds the work capacity, overload will occur resulting in fatigue (Kenny, et al., 2008; Ilmarinen, 2001; Weerding, et

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al., 2005; Costa-Black, et al., 2013; Bos, et al., 2004). To prevent chronic fatigue and maintain the individual balance between workload and capacity, there is a need for objective, valid and reliable measurement tool to monitor energetic workload during work (Faria, et al., 2018; Alberto, et al., 2017) on a non-obstructive manner which does not influence the workability (Catal & Akbulut, 2018; Hoehn, et al., 2018). Thirdly, the energetic workload related aspect heat exposure (internal reaction on external load) (Spook, et al., 2019; Radwin & Lavander, 1999). Heat exposure during physically demanding work, as working in (indoor and outdoor) hot (and humid) environments and the wear of personal protective clothing (PPC) and equipment (PPE), can result in heat strain (internal reaction on heat production and regulation) and heat stress (internal and external load) (McQuerry, et al., 2018; Costello, et al., 2015; Yazdi & Sheikhzadeh, 2014; Nunneley, 1989; Levels, et al., 2014). This heat strain and stress can result in short and long-term health problems as heat exhaustion, dehydration, physical fatigue and loss of consciousness (Chang, et al., 2017; Cvirn, et al., 2019; Epstein & Moran, 2006; McInnes, et al., 2017; Barr, et al., 2010). Heat strain and stress among physically demanding occupations is of major concern and needs to be prevented. However, there is an urge for a continuous, accurate, instrument to monitor core temperature and heat stress development during the performance of the job on a non-invasive and easy-to-use manner (Mazgoaker, et al., 2017; Moran & Mendal, 2002; Chaglla, et al., 2018; McKenzie & Osgood, 2004; Uth, et al., 2016; Steck, et al., 2011).

1.5 | Outline and aims of dissertation

The overarching aim of this dissertation is to contribute to a sustainable workforce by making the (mis)balance between workload and work capacity measurable with sensor technologies. When the workload and work capacity can be monitored, misbalance could be prevented. The focus is on prevention of misbalance by making workers aware of their behaviour by firstly developing and testing sensor technologies to measure workload and capacity objectively, secondly by measuring the workload, and thirdly by providing interventions to increase their work capacity or lower the workload. The objective of the studies in this dissertation is to develop and test sensor technologies that are usable in the workplace and able to monitor (1) working postures and movements and related internal mechanical workload, (2) the internal energetic workload, and (3) internal reaction on external heat exposure. The focus will be on user-centred design, the physical workload of individuals, developments that are personalized, smart, and user-driven and make workers aware of their working behaviour.

In *Chapters 2 and 3*, the focus is on working postures and mechanical workload. *Chapter 2 'Can a smart chair improve the sitting behaviour of office workers?'* is a study of the mechanical workload of office workers. With a smart sensor chair the sedentary behaviour, sitting postures, and duration of sitting of office workers are monitored. Additionally is investigated if a tactical feedback signal could improve this behaviour. This study aimed to (1) investigate the effect of the feedback signal on the sitting behaviour; (2) investigate the effect of the feedback signal on the perceived local musculoskeletal discomfort related to working while seated for a prolonged time; (3) investigate the difference between the measured sitting duration with the smart chair and behaviour measured both in and out of the chair with an activity tracker (sitting duration and amount of steps).

In Chapter 3 '*Automatically determining the moment of the lumbar load during physically demanding work*', the mechanical workload of physically active workers is investigated. With a "sensor suit" and with a specially developed artificial neural network-based method, the backload related to the working postures can be estimated. The aim of this study was to test if this sensor system can distinguish the estimated lumbar load of different intensity and variability levels relative to the perceived task loads using discriminant validity.

To be able to monitor the energetic workload, a mouth mask-less breathing gas analyser has been developed and presented in *Chapter 4 'Patent application of an instrument, system and method for use in respiratory exchange ratio measurement*. In *Chapter 5 'Can breathing gases be analysed without a mouth mask? Proof-of-concept and concurrent validity of a newly developed breathing-gases analysing headset',* this monitoring system is validated. This proof-of-concept study aimed to investigate (1) the validity of $\dot{V}O2$, carbon dioxide production ($\dot{V}CO2$) and respiratory exchange ratio (RER) measurements produced by the developed breathing-gas analysing headset compared to a mouth mask (reference system), (2) the validity of $\dot{V}O2$ measurements produced by the developed breathing-gas analysing headset compared to estimated $\dot{V}O2$ based on HR, (3) the influence of wind on the validity of the system, and (4) the user experience of the developed headset system.

To monitor the heat exposure of physically active workers, in *Chapter 6 'Monitoring core temperature of firefighters to validate a wearable non-invasive core thermometer in different types of protective clothing: concurrent in-vivo validation'*, the accuracy of a wearable thermometer is investigated and the development of the core temperature of firefighters in two types of personal protective clothing is monitored during a simulation exercise. The aims of this study were (1) to test the validity and reliability of a wearable non-invasive core temperature sensor in rest in comparison to an invasive temperature sensor pill and standard inner-ear IR thermometer and (2) during realistic firefighting simulation tasks in comparison to an invasive temperature sensor pill, and (3) to compare the change in core temperature recorded with the wearable non-invasive core thermometer and an invasive temperature sensor pill of firefighters during realistic firefighting simulation tasks in two types (traditional turnout gear versus a new concept) of protective clothing. In chapter 7, *'Evaluation of a wearable non-invasive thermometer for monitoring ear canal temperature during physically demanding work',* the wearable thermometer for monitoring heat stress is investigated and validated in a lab (controlled conditions) and a field (real-life working conditions) study among different types of physically active workers The aims were to (1) test the in-vitro accuracy of the non-invasive thermometer in controlled lab conditions; (2) test the in-vivo accuracy as an inner-ear thermometer in controlled lab conditions; (3) test the in-vivo accuracy of the thermometer during the performance of physically demanding occupations; (4) investigating the influence of the environmental conditions wind, temperature changes and lack of ventilation due to PPC and PPE on the accuracy of the Cosinuss°; and (5) explore the usability to measure inner-ear temperatures during the performance of physically demanding occupations. In Appendix I the results of the in-vitro and in-vivo validity of another newly developed non-*invasive thermometer* CORTES can be found.

Implementation of personalized monitoring technologies in workplaces comes with privacy and responsibility concerns for both workers and employers. In Chapter 8 '*Ethics in design and implementation of technologies for workplace health promoting technologies'*, the ethical considerations behind monitoring workload are evaluated. Despite a comprehensive ethics framework, there is still a lack of knowledge on (1) how to overcome the divide in ethical approaches to designing and implementing innovative technologies, (2) how context can play a role when addressing critical ethical issues such as privacy and autonomy, and (3) how ethical responsibilities of the different stakeholders can be made manifest and used. The aim of this paper is to address these challenges by analysing two ethical issues, privacy, and autonomy of workers, in a real-life research setting.

In *Chapter 9*, sensor technologies and their implementation in the workplace are discussed, considering an evaluation of the results, the relevance of these developments, future research, and perspectives.

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