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Protocols and Test Development for the Evaluation of an Innovative Wearable Interface in the context of Work Related-MSDs

Tesi di Laurea Magistrale in
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Abstract

Work-related Musculoskeletal Disorders (WRMSDs) constitute a major health problem for employees, and the economic consequences are substantial for the individuals, companies and society. In order to reduce the risk of WRMSDs several methods have been developed, accepted by the international literature and used in the workplace. However most of these methods are based on self-reports and observational inspections and have numerous limitations, such as the lack of objectivity, accuracy and reliability. Instrument-based methods instead, rely on direct measurements from sensors attached to the workers body and they are becoming a trend and are more frequently used by experts. Within this category of methods, Smart Work Clothes are pervasive solutions for real time and/or long-term ergonomic assessment and posture biofeedback in the context of WR-MSDs prevention. These devices, without interfering with the typical movements performed by workers at the workplace, would allow the estimation of biomechanical risk in real-time providing a direct feedback to the end-user who would be constantly monitored directly at work. This thesis work is part of the development of a smart garment, more specifically, a sleeveless shirt with eight embedded EMG electrodes that permits to monitor the muscular effort and other features from biological signals during working activities. In order to design and develop the prototype of the smart garment the muscles on which to place the textile electrodes were selected: Upper Trapezius, Infraspinatus, Latissimus Dorsi and Erector Spinae. The four bilateral selected muscles is the result of a cross correlated research between three elements: the main WR-MDSs, the working sectors that mostly report MSDs and the main working activities carried out in those sectors. This allowed to identify the most overload and fatigued muscles during the execution of the working tasks carried out in the sectors with the greatest number of WR-MSDs reported. In order to develop a systematic method, that permits to simulate different working tasks in a laboratory environment, an acquisition protocol was developed. The protocol, composed by several parts and implemented in python, allows to acquire muscle activity, registered during tasks execution, using surface electromyography technique with disposable electrodes and motion capture technology. The aims is to define an elaboration procedure to extrapolate correct patterns of muscle activation and deactivation in order to be used then in next stages of the system development to distinguish correct and incorrect movements and/or working cycles. This framework was validated with 8 subjects, in a simulation of a task based on the *manual handling of low loads at high frequency* where the parameters that defines the task were chosen so as there is no exposure to the common risk factors reported by the *Occupational Safety and Health* Directives and therefore the extrapolated patterns can be defined correct. The results showed that the protocol defined and the data elaboration system implemented provides a promising method to extrapolate correct activity patterns task-based and to be used to conduct future experimental procedures in order to validate the smart garment prototype when ready.

Sommario

I disturbi muscoloscheletrici lavoro correlati (DMS) costituiscono un grave problema di salute per i lavoratori e le conseguenze economiche risultano sostanziali per gli individui, le aziende e la società. Al fine di ridurre il rischio dei DMS sono stati sviluppati diversi metodi, accettati dalla letteratura internazionale e utilizzati sul posto di lavoro. Tuttavia, la maggior parte di questi metodi si basa su schede ti adutovalutazione e ispezioni osservazionali e presenta numerosi limiti quali la mancanza di obiettività, accuratezza e affidabilità. I Metodi oggettivi/strumentali si basano invece su misurazioni dirette provenienti da sensori attaccati al corpo dei lavoratori e vengono sempre più frequentemente utilizzati dagli esperti. All'interno di questa categoria di metodi, gli Smart Work Clothes sono soluzioni pervasive per la valutazione ergonomica e il biofeedback posturale in tempo reale e/o a lungo termine nel contesto della prevenzione dei DMS lavoro correlati. Questi dispositivi, senza interferire con i movimenti tipici dei lavoratori sul posto di lavoro, permettono la stima del rischio biomeccanico in tempo reale fornendo un feedback diretto all'utente finale che sarebbe costantemente monitorato sul posto di lavoro. Questo lavoro di tesi fa parte dello sviluppo di un dispositivo indossabile, nello specfico costituito da una maglia senza maniche con otto elettrodi EMG incorporati che permette di monitorare lo sforzo muscolare durante lo svolgimento delle attività lavorative. Per progettare e sviluppare il prototipo dell'indumento sono stati selezionati i muscoli su cui posizionare gli elettrodi tessili: trapezio superiore, infraspinato, grande dorsale e muscolo spinale. I quattro muscoli bilaterali selezionati sono il risultato di una ricerca incrociata tra tre elementi: i principali DMS lavoro correlati, i settori lavorativi che riportano il maggior numero di DMS e le principali attività lavorative svolte in quei settori. Ciò ha permesso di identificare i muscoli che sono tendenzialmente più sovraccarichi e affaticati durante l'esecuzione delle mansioni lavorative svolte nei settori con il maggior numero di MSD segnalati. Al fine di sviluppare un metodo sistematico, che consenta di simulare diversi compiti di lavoro in un ambiente di laboratorio, è stato sviluppato un protocollo di acquisizione. Il protocollo, composto da diverse parti e implementato in Python, permette di acquisire l'attività muscolare, registrata durante l'esecuzione di compiti lavorativi, utilizzando l'elettromiografia di superficie e sistema di analisi del movimento. Lo scopo è quello di sviluppare una procedura per estrapolare schemi corretti di attivazione e disattivazione muscolare da utilizzare poi nelle fasi successive dello sviluppo del sistema per distinguere movimenti e/o cicli di lavoro corretti e scorretti. Questo framework è stato validato con 8 soggetti, in una simulazione di un compito basato sulla movimentazione manuale di bassi carichi ad alta frequenza dove i parametri che definiscono il compito sono stati scelti in modo tale che non vi sia esposizione ai comuni fattori di rischio riportati dalla Sicurezza sul Lavoro e Direttive Sanitarie in modo che i pattern estrapolati fossero effettivamente corretti. I risultati hanno mostrato che il protocollo definito e il sistema di elaborazione implementato forniscono un metodo promettente per estrapolare modelli di attività corretti basati sulle attività e da utilizzare per condurre future procedure sperimentali al fine di convalidare il prototipo quando sarà pronto.

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1 | Introduction

According to international statistics, in the last years Work-Related Musculoskeletal Disorders (WR-MSDs) have become one of the main concern for workers health and safety: only among the working population in the EU approximately three out of every five workers in the EU-28 reported MSD complaints in the back, upper limbs and/or lower limbs [1]. MSDs are defined as a series of disorders and pathologies affecting the osteoarticular, musculotendinous, nervous and vascular systems that can be caused and/or aggravated by biomechanical work overload. WR-MSDs are in general not caused by one specific, but by multiple risk factors. These include physical (e.g. manual handling of loads, working in awkward postures, repetitive work and working at high speed, exposure to vibrations) as well as psychosocial (work stress) demands [2]. MSDs are a major cause of concern: first of all because they affect the general health situation of so many workers, and secondly because of the economic impacts on enterprises and the financial and social costs to European countries.

In order to reduce the risk of WR-MSD several methods have been developed, accepted by the international literature and used in the workplace and they can be gathered in three groups: self-reports, observational inspection or by instrument-based techniques [3]. Self-reports methods usually consist of questionnaires that must be filled by the monitored workers. Those methods are easy to use but they are prone to give a distort information due to the subjectivity of the worker perception. Observational inspection consists of the visual analysis of recording observations with the help of pro-forma sheets. This category of methods focus mainly on postural observation, workload or a combination of the two. Among these methods some of the most adopted are the *Rapid Upper Limb Assessment* (RULA) [4], *NIOSH Lifting Index* [5] *Job Strain Index* (SI) [6] and *Occupational Repetitive Action Index* (OCRA) [7]. These methods enable overall indices or scores for combinations of exposure factors to be determined with the aim of prescribing acceptable exposure limits for workers, or at least establishing priorities for intervention across a range of tasks. The epidemiological data upon which these scoring systems are based is limited particularly with respect to how different factors should be weighted, or interactions between factors should be quantified. The scoring systems are therefore largely hypothetical [3].

Instrument-based techniques indeed, rely on direct measurements from sensors attached to the workers body and they are becoming a trend and are more frequently used by experts. The majority of the available devices are sensor systems composed of different types and numbers of sensors located in diverse body parts such as surface EMG, IMUs, Exoskeletons and Motion Analysis systems, among others. Among the instrument based methods, wearable devices are pervasive solutions for increasing work efficiency, improving workers' well-being [8], reduce work-related injuries and creating interactions between users and the environment [9].

In this context, the WINGS (Wearable Industrial Gear) system designed by LWT3 was born with the purpose to reduce musculoskeletal injuries and enhance the collaborations between workers, machines and co-Bots. WINGS is an under development wearable system which consists of a washable smart garment with embedded textile electrodes and electronic component for signal processing and transmittance in order to monitor the muscular effort during working activities. The structure of the system allows the acquisition, analysis and display of data concerning the user, the machine and preferably also the environment in which they are, so as to improve the quality of life of the operator and of the production processes.

This thesis work, carried out at the LWT3 Laboratory, is part of WINGS R&D process and my contribution to this project consists of two main phases.

The first part consists in the support gave to the design team in order to design and develop the first prototype of the smart vest selecting the muscles on which to place the textile electrodes. The four bilateral selected muscles is the result of a deep literature and statistical research in terms of correlation between three elements: the main Musculoskeletal Disorders in work environment, the working sectors that are mainly affected by absenteeism due to MSDs and the main working activities carried out in those sectors, in order to identify the most overload and fatigued muscles during the execution of the previously identified working tasks. The muscles on which to place the electrodes are established also considering the design constraints dictated by the company. This part sees also the implementation of a series of tests to find the correct placement and orientation of the selected muscles.

The WINGS system will allow to warn the operator of possible dangers to his health, in real time and/or on a long-term and thus the system need to be trained to discern the wrong movements from the correct ones, in order to assess in real time the working activities. In view of this purpose, the second part of this thesis focuses on the development of an acquisition Protocol that permits to simulate different working tasks, such us lifting of loads, handling of low loads at high frequency, pushing and pulling, work in prolonged standing posture, etc., aiming at gathering correct muscular activity patterns task-correlated. The Protocol represents a systematic method that permits to LWT3 to acquire and process information on different working activities. Finally a simulation of a task based on the *manual handling of low loads at high frequency*, as defined by EU and international regulations on safety in the workplace, is conducted in order to validate the Protocol as a replicable methodology that permits to be used by LWT3 in the next stages of the system development.

The following thesis work consists of eight chapters.

Chapter 2 describes the Epidemiology of Musculoskeletal Disorders, in particular it exposes their prevalence, the impact on health and social costs, the risk factors correlated to Work-related Musculoskeletal Disorders (WR-MSDs) and finally the types of WR-MSDs on back, upper limb and lower limb.

Chapter 3 reports the state of the art of the current methods developed and used for WR-MSDs assessment and prevention, highlighting their advantages and disadvantages. A review of the current methodologies will be discussed, focusing on the instrument based methods and in particular on the wearable devices. This chapter provides also information about the European Directives regarding the principles of prevention and risk assessment at work to be adopted.

Chapter 4 presents the principles of electromyographic signal (EMG), its generation and recording, focusing on the surface EMG technique. The chapter also reports the commonly used methods for electromyographic signal analysis and processing.

Chapter 5 deals with the framework and objective of this thesis describing the system under development by LWT3 and my contributions in the design and development of the system.

Chapter 6 and Chapter 7 present respectively the materials and methods of the experimental procedures and the data elaboration processes.

Chapter 8 reports and discusses the results for each of the methods implemented.

Chapter 9 provides the conclusions of the work carried out and the future implementations.

2 | The Musculoskeletal Disorders

Musculoskeletal disorders and biomechanical overload, as confirmed by national and international statistics, have in recent years become a major concern for the health and safety of workers. This is not only because of the quantitative data relevant to the cases statistically recorded, but also because of their peculiar transversality to many working sectors. Musculoskeletal disorders include a wide variety of inflammatory and degenerative conditions of muscles, tendons, ligaments, joints, peripheral nerves and vascular structures. Although not necessarily work-related, they are the largest category of occupational diseases in developed countries. This chapter, after defining the musculoskeletal disorders and their prevalence, discusses the impact on economic and health point of view. Finally, the risk factors and the types of work related MSDs are presented.

2.1. Definitions and Concepts

MSDs is an umbrella term for medically established periarticular diseases of the limbs and spine, and for multiple or localized pain syndromes [10]. There are several definitions in the academic and scientific environment, within which [11], these particular occupational diseases are referred to as "a heterogeneous group of disorders many of which are only vaguely known". The European Agency for Health and Safety at Work (EU-OSHA), however, defines them as "a vast complex of diseases and inflammatory and degenerative disorders that result in pain and functional limitation", while in Italy the definition is that of the Ergonomics of Posture and Movement (EPM) that catalogues them as "alterations of the muscle-tendon units, nerves and vascular system, aggravated by repeated movements and/or efforts of the upper limb". In the light of these three definitions of international, european and national level, it is possible to infer how these particular disorders are not well defined in kind and especially in their manifestation, representing significant limits in the management of prevention and verification of the causal link in the case of pathological manifestations. MSDs can range from those that arise suddenly and are short-lived, such as fractures, sprains and strains, to lifelong conditions associated with ongoing functioning limitations and disability [12]. When MSDs are caused or aggravated primarily by work itself, these can be defined as work-related MSDs (WRMSDs). Work-related MSDs arise from regular exposure to a certain load and it is a problem that affects all forms of working environments, from physically arduous work to low-intensity static work [13], [14]. These disorders, unlike the "specific occupational diseases" [15], for which there is a direct cause-effect between a harmful agent and the disease, are defined by the WHO as "diseases with multifactorial etiopathogenesis" as they are also found in the non-exposed population and caused, according to medical literature, by additional extra-occupational factors such as aging, previous traumatisms, chronic pathologies (diabetes, hypothyroidism, rheumatoid arthritis or other situations such as menopause, pregnancy or the assumption of oral contraceptives), movements performed incorrectly and repeatedly during sports and / or hobby activities [10], [12]. It is clear, therefore, that the genesis of these particular disorders may have different origins and not strictly related to work. For this reason, in order to consider musculoskeletal disorders and biomechanical overload pathologies as work-related occupational diseases, it is necessary to verify the existence of risk factors as identified and distinguished by the EU-OSHA. The European Agency believes that there are two macro classifications of specific risk from work, in which on the one hand there are physical risk factors, where every reference is made to the way in which the work is carried out considering the task of attribution, and on the other hand there are listed the environmental and organizational risk factors, as additional elements that affect or may affect the manifestation of pathologies constituting real work-related causes if we consider the physical risk factors as the main causes of work-related [2]. The risk factors for WR-MSDs are discussed in the section 2.4 of this chapter.

2.2. Prevalence of Musculoskeletal Disorders

A recent analysis of Global Burden of Disease (GBD) data showed that approximately 1.71 billion people globally have musculoskeletal conditions [16]. While the prevalence of musculoskeletal conditions varies by age and diagnosis, people of all ages everywhere around the world are affected. Musculoskeletal conditions are the biggest contributor to years lived with disability (YLDs) worldwide with approximately 149 million YLDS, accounting for 17% of all YLDs worldwide. One YLD represents the equivalent of one full year of healthy life lost due to disability or ill-health. Low back pain is the main contributor to the overall burden of musculoskeletal conditions with 568 million people globally. Other contributors to the overall burden of musculoskeletal conditions include [16]:

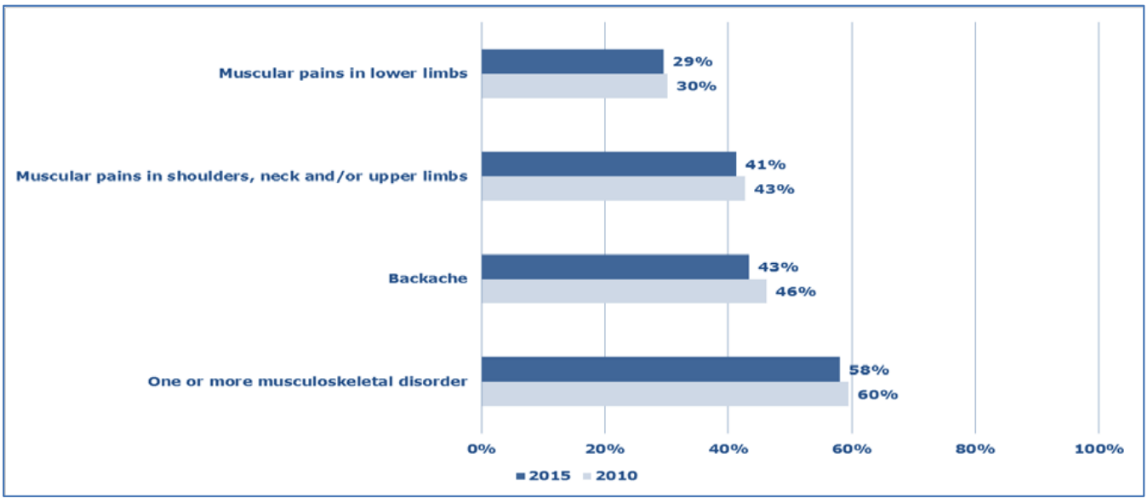
- fractures with 436 million people globally,

- osteoarthritis (343 million),
- neck pain (222 million),
- amputations (175 million),
- rheumatoid arthritis (14 million).

2.2.1. EU framework

MSDs are a major cause of concern since they affect the general health of many workers, and they have large economic impacts on organisations with great social costs in several European countries. As concerns the prevalence of MSDs among the working population in the EU, one of the main sources of information and data regarding MSDs are surveys based on self-reporting where people are asked whether or not they suffer from an MSD. In 2015, approximately three out of every five workers in the EU-28 reported MSD complaints in the back, upper limbs and/or lower limbs. This can be concluded from the sixth wave of the European Working Conditions Survey (EWCS) [1]. The most common MSD types among workers in the EU-28 are backache and muscular pains in the upper limbs (43% and 41%, respectively, in 2015). Muscular pains in lower limbs are reported less often (29% in 2015) (Figure 2.1)[2].

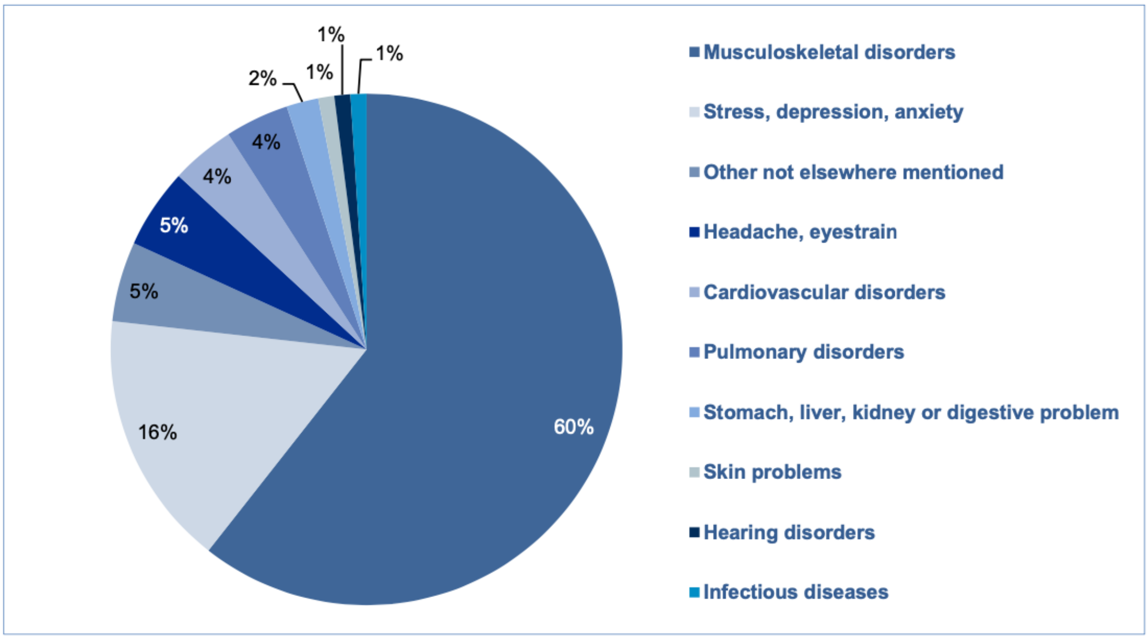
Figure 2.1: Percentage of workers reporting different musculoskeletal disorders in the past 12 months, EU- 28, 2010 and 2015.



N = 33,173 (2010); N = 31,612 (2015).
Source: Panteia based on the fifth (2010) and sixth (2015) waves of the European Working Conditions Survey (EWCS) [1]

As concerns specifically the WR-MSDs the most recent EU-wide data on the prevalence are based on the 2013 ad hoc Labour Force Survey (LFS) module. This module provides information about the proportion of workers who report MSDs as their most serious work-related health problem. Of all workers who mentioned that they suffered from any work-related health problem during the past 12 months, 60% mentioned MSD-related complaints as their most serious health problem (Figure 2.2)[2].

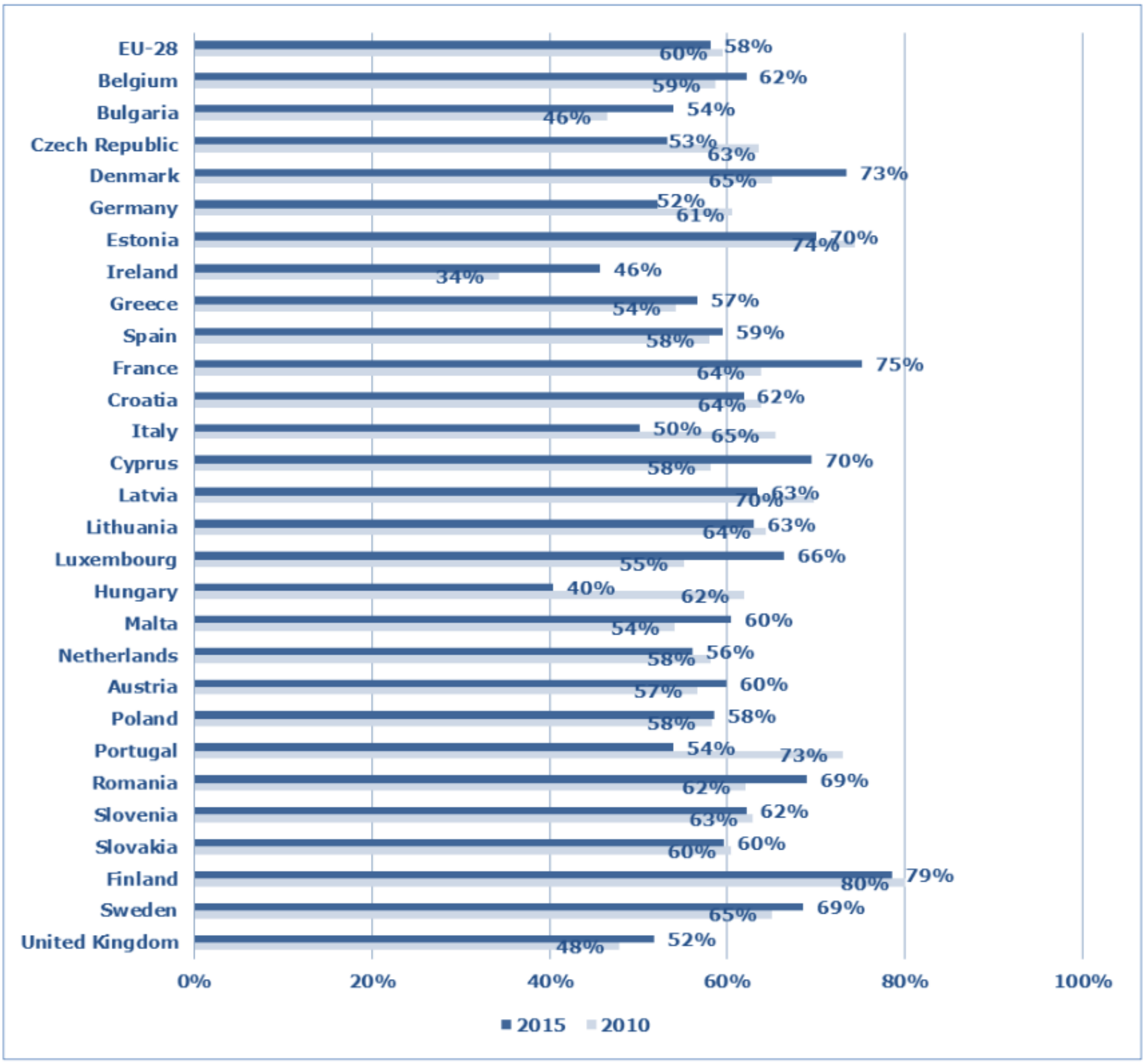
Figure 2.2: Percentage of workers reporting a work-related health problem, by type of problem, EU-27, 2013



The population of workers includes everybody aged 15 to 64 who was working or had worked during the past 12 months before the survey took place.
Source: Eurostat, Labour Force Survey ad hoc module 'Accidents at work and other work-related health problems' (2013). All EU Member States participated in this ad hoc module except for the Netherlands.

Data from Member States At EU level, the prevalence of MSDs hardly changed between 2010 and 2015. Based on the EWCS [1], which investigates three MSD types, in 2015 58% of workers in the EU-28 reported that they had suffered from one or more of these MSDs during the past 12 months. Five years earlier, the percentage was almost the same (60%). At the level of individual countries, there is, however, a lot of variation (Figure 2.3). Variation exists both between countries and within countries across time. It is difficult to find an explanation for these country differences: they are hardly related to differences in the sectoral or occupational distribution of the workforce or to differences in terms of age, gender, education level and country of birth of the workforce [2].

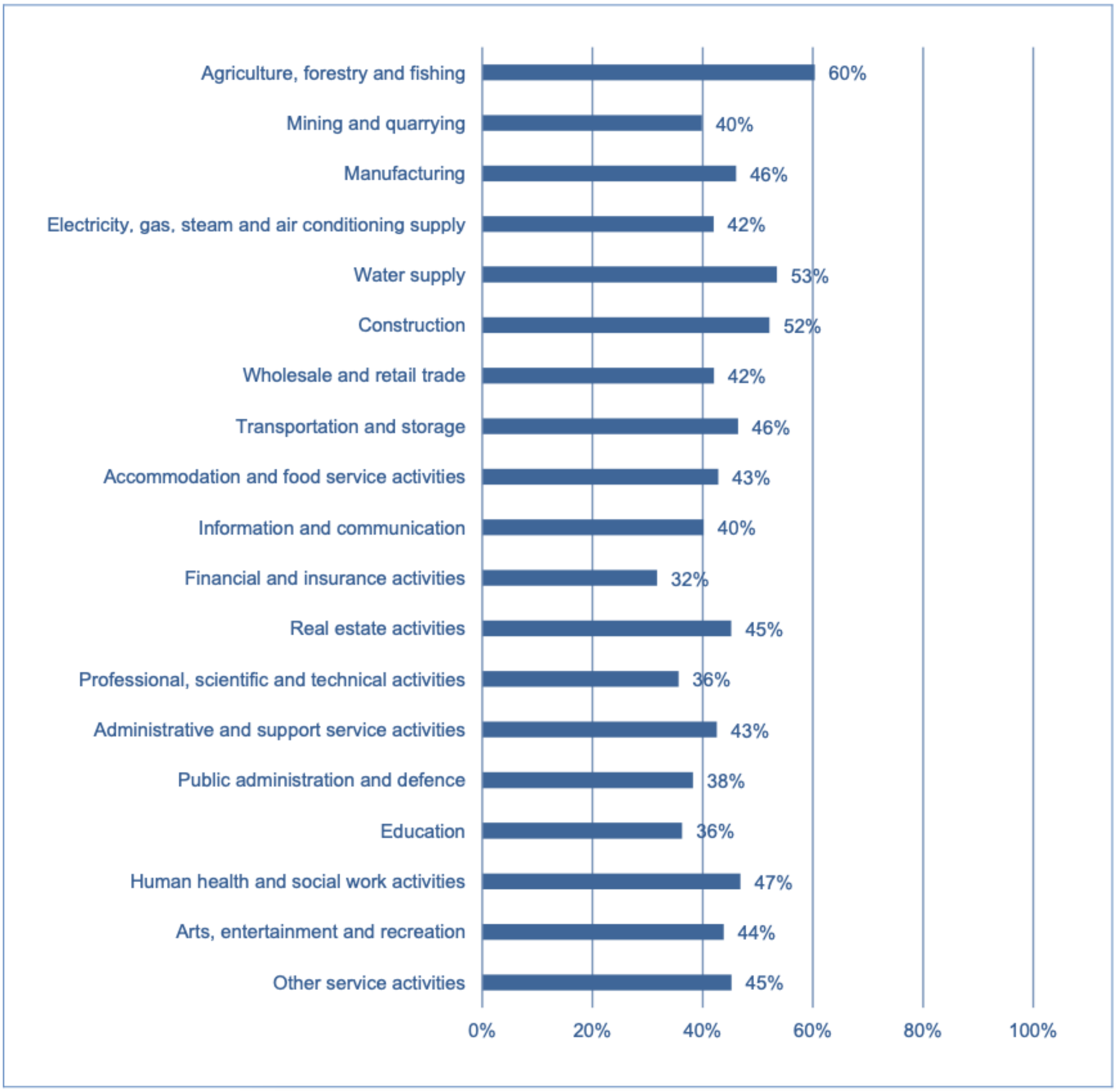
Figure 2.3: Percentage of workers reporting that they suffer from one or more musculoskeletal disorders in the past 12 months, by country, 2010 and 2015



N = 33,173 (2010); N = 31,612 (2015)
Note: 'Musculoskeletal disorders' refers to backache and/or muscular pains in shoulders, neck, upper limbs and/or lower limbs (hips, legs, knees, feet, etc.).
Source: Panteia based on the fifth (2010) and sixth (2015) waves of the European Working Conditions Survey (EWCS)

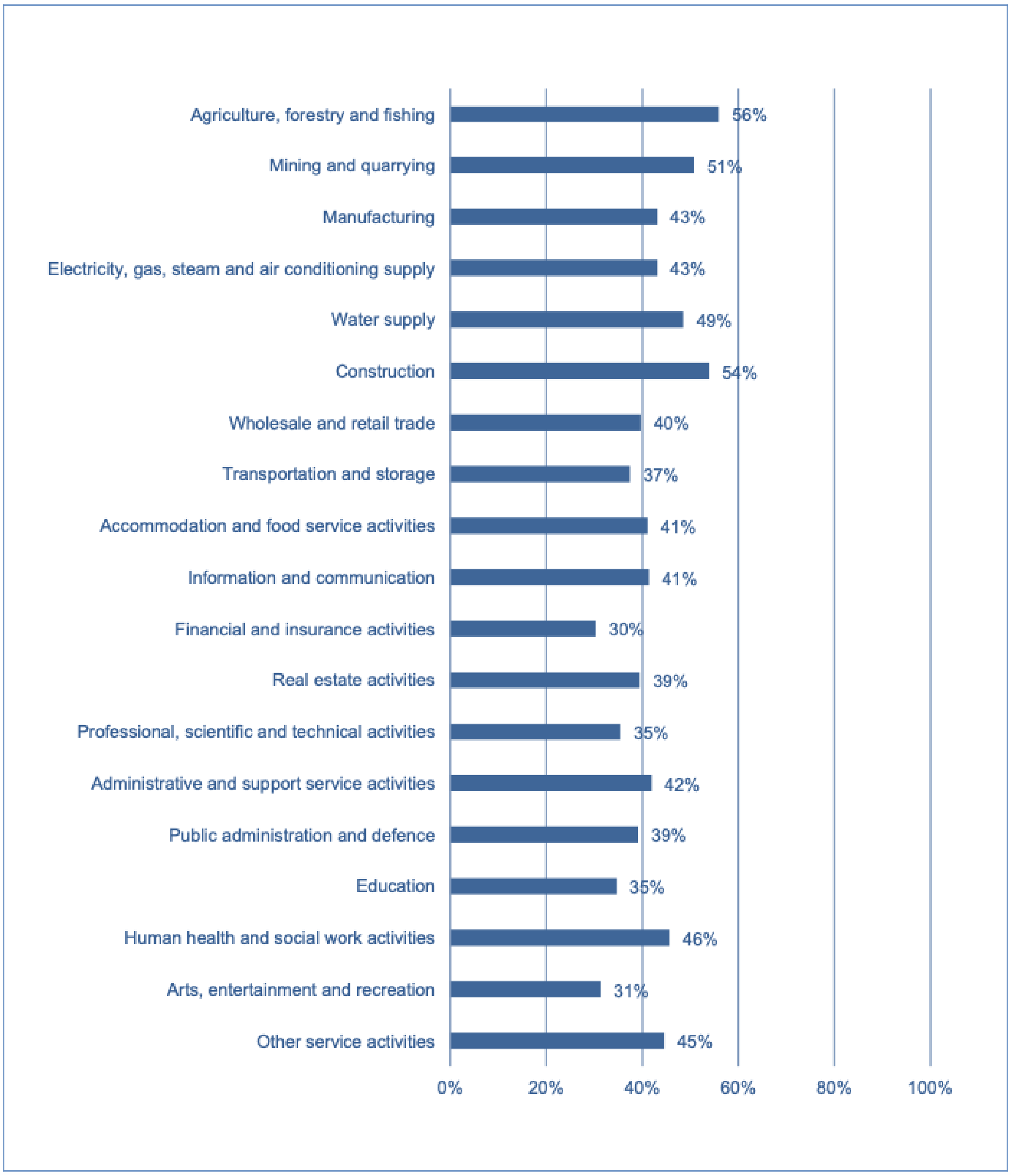
Prevalence by sector The prevalence of self-reported MSDs shows significant differences between sectors (see Figure 2.4 for backache, Figure 2.5 for MSDs in the upper limbs and Figure 2.6 for MSDs in the lower limbs). The prevalence of MSDs is above average in sectors such as construction and agriculture. For example, the percentage of workers reporting backache is 52% in construction workers and 60% for agriculture workers, while the EU average is 46%. MSDs are reported least often in financial and insurance activities and in the education, arts, and entertainment and recreation sectors.

Figure 2.4: Percentage of workers reporting backache in the past 12 months, by sector (Statistical Classification of Economic Activities in the European Community, NACE, rev. 2), EU-28, 2015



N = 35,536
Source: Panteia based on the sixth (2015) wave of the European Working Conditions Survey (EWCS)

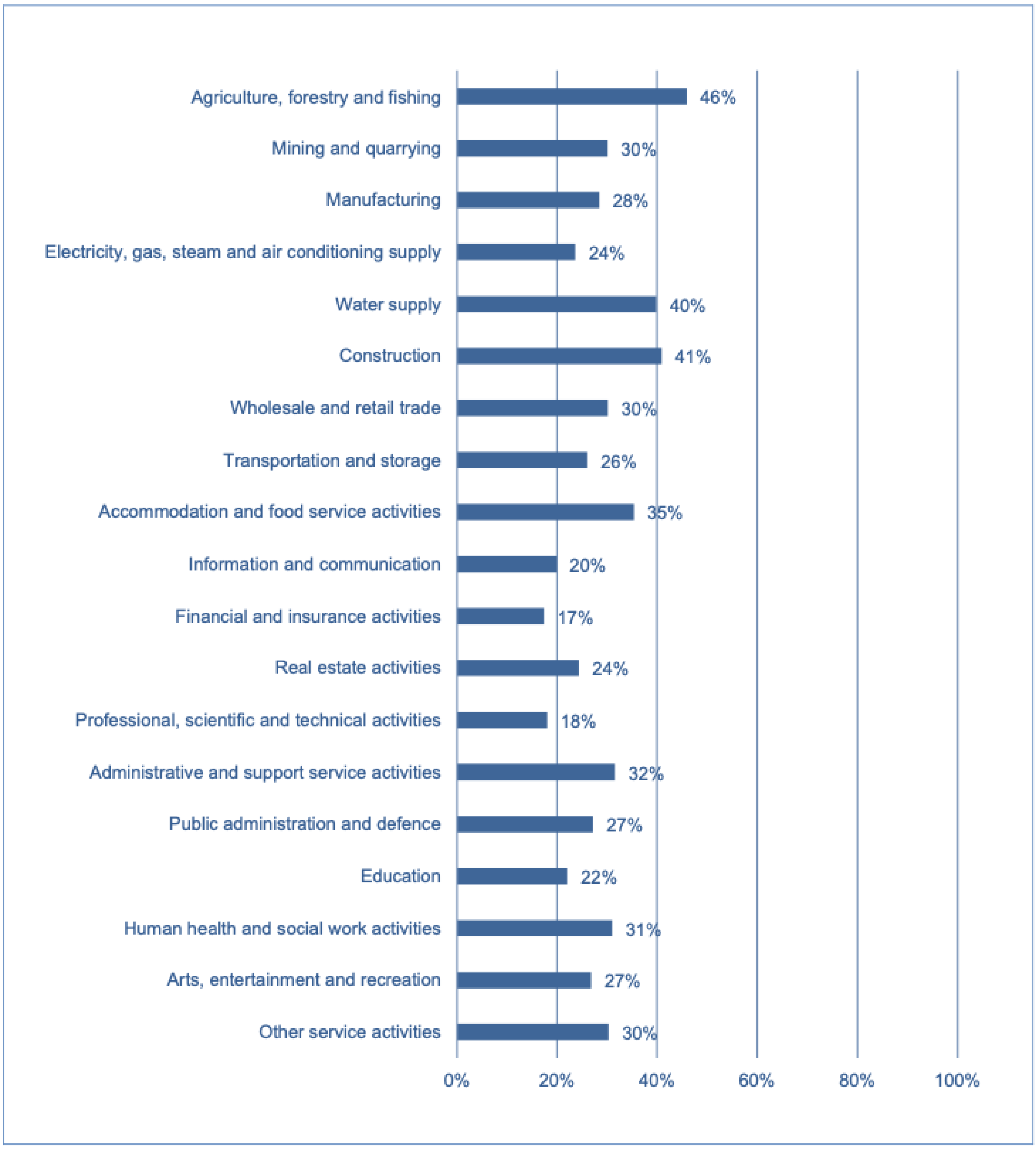
Figure 2.5: Percentage of workers reporting MSDs in the upper limbs in the past 12 months, by sector (NACE rev. 2), EU-28, 2015



N = 35,536

Source: Panteia based on the sixth (2015) wave of the European Working Conditions Survey (EWCS)

Figure 2.6: Percentage of workers reporting MSDs in the lower limbs in the past 12 months, by sector (NACE rev. 2), EU-28, 2015



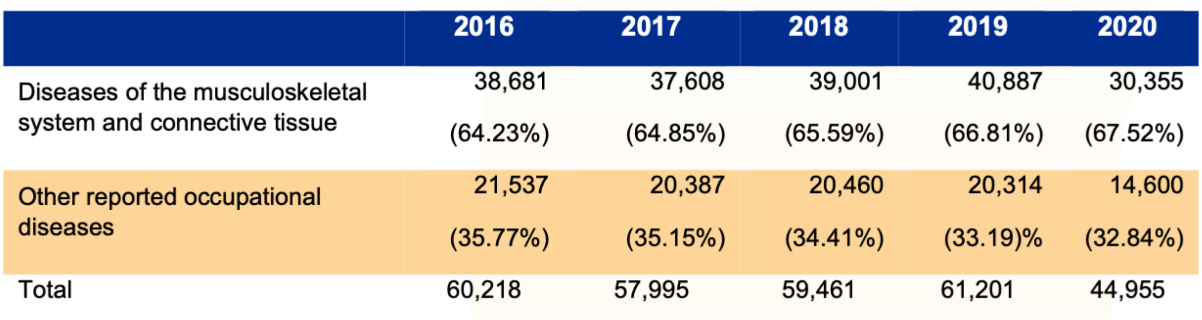
N = 35,536

Source: Panteia based on the sixth (2015) wave of the European Working Conditions Survey (EWCS)

2.2.2. MSDs at National Level: the case of Italy

Italian data on occupational diseases shows that MSDs are the main work-related diseases affecting the Italian workforce. According to the INAIL's report on accidents and occupational diseases [17], MSDs in the workplace is a growing phenomenon in Italy. In 2008, MSDs accounted for less than 40% of the total reported occupational diseases, while their incidence was almost 70% in 2020. The Table 2.1 shows data relating to total reports of occupational diseases in Italy compared with those relating to the musculoskeletal system in the last 5 years. It should be noted that the latter have steadily grown from 64.23% in 2016 to 67.52% in 2020 [17], [18].

Table 2.1: Total reports of occupational diseases in Italy compared with those relating to the musculoskeletal system in the last 5 years



	2016	2017	2018	2019	2020
Diseases of the musculoskeletal system and connective tissue	38,681 (64.23%)	37,608 (64.85%)	39,001 (65.59%)	40,887 (66.81%)	30,355 (67.52%)
Other reported occupational diseases	21,537 (35.77%)	20,387 (35.15%)	20,460 (34.41%)	20,314 (33.19)%	14,600 (32.84%)
Total	60,218	57,995	59,461	61,201	44,955

Source: Adapted from INAIL, 2021a. [17]

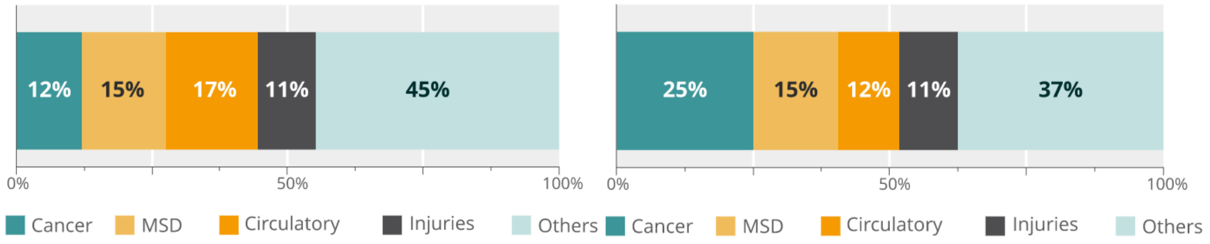
2.3. Impact of MSDs

MSDs are a major cause of concern: first of all because they affect the general health situation of so many workers, and secondly because of the economic impacts on enterprises and the financial and social costs to European countries. These 2 aspects are discussed in section 2.3.1 and section 2.3.2 respectively.

2.3.1. Impact on Health

Musculoskeletal conditions are among the most widespread diseases that affect people of all ages and ethnic groups, causing disabilities and often handicaps.These conditions affect people of all ages. The principal measurement of the burden of disease, Disability Adjusted Life Years (DALYS), is a measure of disease related morbidity and mortality. DALYs reflect the effect of diseases on general population in terms of quality of life and death. MSDs are the second-ranked work-related illnesses in DALYs [2]. DALYs for an illness or health condition are calculated as the sum of the years of life lost due to premature mortality in the population and the years lived with disability (YLD) for people living with the health condition or its consequences. In other words, DALYs indicate the gap between current health status and an ideal situation in which individuals live into old age without disease and disability. The figure 2.7 depict the proportion of the main work-related illnesses and DALYs per 100,000 workers globally and in the EU-28. Cancer, reaching 25%, accounts for the main part of the cost, and musculoskeletal disorders follow at approximately 15%.

Figure 2.7: Percentage of the main causes for work-related mortality and morbidity in DALYs per 100,000 employees. Source: ILO, 2017



(a) Global estimate (b) EU-28 estimate

Workers with MSD-related problems are likely to report that their daily activities are restricted by their health problems. Apart from musculoskeletal pain, suffering from MSDs is associated with other health problems such as anxiety, sleeping problems and overall fatigue, and with lower levels of mental wellbeing. In the long term, workers with MSDs might not be able to continue to do their job or a similar one because of these disorders [2].

2.3.2. Economic Impact

If MSDs affect the general health of workers, it stands to reason that they also affect their performance at work. Workers suffering from MSDs are among those most likely to be absent from work for long periods or to be recognized with a workplace disability [19]. The productive capacity of workers can be affected in two ways: MSDs may reduce the production that workers can realize in an hour (their productivity), and MSDs may reduce the number of hours they can work (e.g. absenteeism, high stuff turnover) [2]. These are the so-called indirect costs, and they exceed the direct health costs; according to the European Agency for Safety and Health at Work, the overall cost is somewhere in the region of 2% of the EU's GDP [19] [2]. DALYs reflect the effect of diseases on general population in terms of quality of life and death. Even though DALYs do not indicate economic values directly, the impact on productivity could be linked to economic loss [20]. MSD add up to a total of 15% of these losses [2]. Direct costs are incurred when resources are used to diagnose and treat the diseases (costs of health care and medicines). Indirect costs are estimated with regard to a loss of production caused by early deaths, reduced ability to work and sick leave. The loss of production was calculated based on the average salary.

Data from Member States At the national level some studies are available that show the impact of MSDs in economic terms (loss of productivity and higher social expenses).

- **Italy** An Italian study [21] was conducted to estimate the number of benefits provided and the associated pension costs incurred by the community for MSCs (in Italy the social security system is funded by the state). Data were taken from the INPS database between 2009 and 2012 that includes 18 diseases in the category of MSCs, among which rheumatoid arthritis (RA) and ankylosing spondylitis (AS). In this range of time about 393 thousand treatments were paid for a total of approximately EUR 2.7 billion. The annual number of treatments was on average 98 thousand and cost in total EUR 674 million per year. The productivity loss for RA in 2013 was equal to EUR 707,425,191 due to 9,174,221 working days lost. From 2009 to 2012, in Italy, the highest indirect costs were associated with disability pensions (54% of the total indirect cost), followed by disability benefits (44.1% of cost) and incapacity pensions (1.8% of cost).
- **Austria** National data from Austria suggest that MSDs represent the third most common cause of sick leave (13% of all cases). MSDs account for 21% of total workdays lost in 2016. The average duration of sick leave caused by MSDs was 15.8 days, well above the general sick-leave period in Austria (around 10 days) [22]. MSDs were the main cause of new health-related retirement pensions in the years 2001 and 2006. MSDs were responsible for 32.5% of these new pensions in 2006 [23].
- **Finland** According to the Finnish social security system (KELA) data for 2017, Finland incurred EUR 63.8 million in medical expenses related to MSDs, of which EUR 28.6 million was reimbursed by KELA. In terms of rehabilitation expenditures, data from KELA show that the total MSD-related expenditure was EUR 41.5 million or 10.9% of the total, the third largest amount, after the rehabilitation expenditures incurred for mental/behavioral disorders and diseases of the nervous system (data for 2017) [24].
- **France** In France, work-related lower back pain resulted in 12.2 million lost work-

days, or 57,000 full-time equivalents. Estimates of the direct annual costs borne by companies exceed EUR 1 billion per year through their contributions to occupational accidents and diseases, while more than half (EUR 580 million) is related to sick day compensation (data for 2017) [25]. Indirect costs of MSD-related problems include costs due to disruptions in working teams, decreases in productivity, production delays, etc. According to the French National Research and Safety Institute for the Prevention of Occupational Accidents and Diseases (INRS), these indirect costs could be up to 10 times higher than the direct costs for businesses [25].

- **Germany** According to BAuA (Federal Institute for Occupational Safety and Health), MSDs produce the highest costs compared with all other disease diagnosis groups. It is estimated that EUR 17.2 billion production loss (production loss costs based on labour costs) and EUR 30.4 billion loss of gross value added (loss of labour productivity) arise from diseases of the musculoskeletal system. This represents 0.5% and 1.0% of Germany's gross domestic product (GDP), respectively (data for 2016) [26] . Musculoskeletal and connective tissue disorders are the second most common disease behind access to new pensions due to reduced working capacity in Germany, after psychological/behavioural disorders (10,938 new pensions among men and 11,878 among women). Access to new pensions due to MSDs and connective tissue disorders increased between 2014 and 2016 [2], [26].

- **Spain** According to a study [27] that estimated the annual cost of temporary work disability caused by MSDs in Spain, MSDs were the leading cause of temporary work disability in 2007, representing 18% of the total (908,781 cases), 23% of all lost working days (39,342,857 in total) and 23% of the total costs related to temporary work disability (EUR 1.702 billion in total), which is estimated at EUR 1.62 per EUR 1,000 of national GDP.

- **Sweden** In Sweden, MSDs are the most common reason for illness and absence from work: around 957,000 Swedes over 16 years old suffered from some form of MSD-related complaint in 2012, and such diseases are more prevalent among people over 45 years old. Approximately 20-30% of all visits to Swedish public health care were caused by MSDs and that MSDs accounted for 11% of total healthcare costs in Sweden (data for 2012)[28]. Regarding direct and indirect costs of MSDs, the total costs for society connected to MSDs were approximately EUR 9.9 billion, which can be translated into 2.8% of the national GDP for 2012. The numbers presented above are most likely an underestimation of the total costs for society, since there are elements regarding MSDs that are very difficult to estimate in monetary terms. Osteoarthritis and back diseases together accounted for 60% of the sick leave and

64% of the costs of MSDs. In total, MSDs caused 450,000 days of absence from work distributed among 78,500 people [28].

2.4. Risk Factors for Work Related Musculoskeletal Disorders

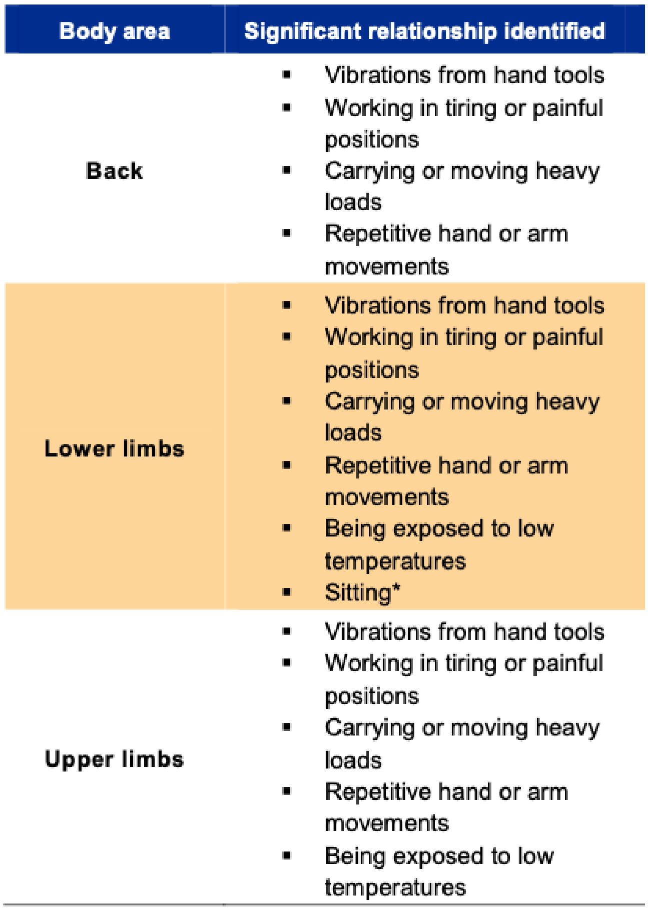
The causes of work-related MSDs are multifactorial and there are numerous work-related risk factors for the various types of MSDs. Several risk factors including physical and mechanical factors, organisational and psychosocial factors, individual and personal factors may contribute to the genesis of MSDs. Workers are generally exposed to several factors at the same time and the interaction of these effects are often unknown [29]. The objective of this section is to discuss the current knowledge of the role and prevalence of various risk factors at work. With regard to physical risk factors, studies have found reasonable evidence for an association between different types of MSDs and the following physical risk factors [2]:

- posture and working in awkward positions;
- heavy physical work;
- lifting;
- repetitive work;
- prolonged computer work.

Consistent with these findings, analyses on EWCS data show that prevalence of MSDs is associated with working in tiring or painful positions, carrying or moving heavy loads and repetitive hand or arm movements. This applies to all three types of MSDs that are distinguished in the EWCS (back, upper limbs and lower limbs). In addition, being exposed to vibrations from hand tools also increases the likelihood of reporting any of these three types of MSDs. Being exposed to low temperatures is associated with a higher prevalence of MSDs in upper limbs and lower limbs. The results of the analyses on the sixth wave of the EWCS are summarised in Table 2.2.

Table 2.2 shows that MS disorders can be associated with a variety of workplace and work characteristics (physical load, work environment, work organisation and psychosocial factors). Also individual factors such as health status, age and gender have an impact [19]. Sections 2.4.1, 2.4.2 and 2.4.3 deeply discusses the main risk factors for WR-MSDs.

Table 2.2: Associations between self-reported MSDs and physical risk factors



Body area	Significant relationship identified
Back	▪ Vibrations from hand tools ▪ Working in tiring or painful positions ▪ Carrying or moving heavy loads ▪ Repetitive hand or arm movements
Lower limbs	▪ Vibrations from hand tools ▪ Working in tiring or painful positions ▪ Carrying or moving heavy loads ▪ Repetitive hand or arm movements ▪ Being exposed to low temperatures ▪ Sitting*
Upper limbs	▪ Vibrations from hand tools ▪ Working in tiring or painful positions ▪ Carrying or moving heavy loads ▪ Repetitive hand or arm movements ▪ Being exposed to low temperatures

* For prolonged sitting, the relationship to the prevalence of self-reported MSDs (in the lower limbs) is negative. For all other risk factors mentioned in the second column of this table, the relationship to the prevalence of self-reported MSDs is positive. Source: Panteia, 2019.

2.4.1. Physical Load

There are several occupational risk factors resulting in high mechanical loads on the neck, shoulder and upper limbs.

Force exertion Sustained or excessive force results in heavy mechanical loads on the neck, shoulders and upper limbs: handling objects, using tools, fast movements or excessive force generated by the muscles of the body, local force and stress from items coming into contact with parts of the upper limbs. Force is the amount of effort required to perform a task or a job. It depends on someone's posture and the number of exertions performed. As a higher force is exerted, the stress on the body is higher. Not only is the intensity of effort harmful but also its duration.

Repetitive movements Repetitive movements are especially hazardous when they involve the same joints and muscle groups over and over again and whenever the same movement is done too often, too quickly and for too long. Analysing the repetitiveness of a task involves the steps or cycles it takes. Work involving repetitive movements is very tiring because the worker cannot fully recover in the short periods of time between movements. If the work activity continues in spite of the fatigue, injuries can occur. The cycle duration is significant if less than 30 seconds or if the repetitive movements account for 50% of work time.

Working posture Poor posture and uncomfortable working posture: any body position can cause discomfort and fatigue if it is maintained for long periods of time, but certain tasks can make workers use unnatural standing positions. Uncomfortable working posture or awkward postures represent unnatural positions, deviated from “neutral positions”, in which joints are held or moved away from the body’s natural position. The closer the joint is to its end of range of motion, the greater the stress placed on the soft tissues of that joint, such as muscles, nerves, and tendons. When muscles are contracted, the body is subjected to a greater mechanical effort. Joint positions of the upper limb, when working outside comfort angle, increase the possibility of WRMSDs, regardless of effort intensity or degree of repetition.

2.4.2. Work Environment

Besides heavy physical work and repetitive work, that constitutes the main physical hazards for MSDs, other physical factors making the working environment uncomfortable might also play a role in the development of MSDs. The World Health Organization defined work-related MSDs as a problem of the locomotor apparatus resulting from a number of factors and strongly affected by the work environment and the circumstances of work performance [30]. The following factors impact significantly on the development and exacerbation of MSDs [31], [32]:

- Poor workspace layout, poor design of tools and machinery can result in adopting stressful working postures and applying force;
- Temperature of the workplace affects the body muscles: excessive heat increases overall fatigue and produces sweat which makes it hard to hold tools, requiring more force; excessive cold can make the hands feel numb, making it hard to grip and requiring more force; every movement and position involving more effort are more likely to develop work-related neck and upper limb disorders (WRULDs).

- Poor lighting can create glare or shadows that may require workers to adopt awkward positions to see clearly what they are doing;
- High levels of noise may cause the body to tense in static body postures resulting a more rapid onset of fatigue;
- Vibration can cause damage to nerves and blood tissues as well as other soft tissues. Hand-arm vibrations cause tingling and numbness, or loss of sensibility, requiring a higher clamping force and awkward body positions because vibration hand tools are harder to control.

The risk of injury increases when two or more WRMSDs risk factors are combined in one job; moreover, task duration in each shift plus the number of working days the task is performed, determine the risk level.

2.4.3. Organizational and Psychosocial Factors

Previous studies have found reasonable evidence for an association between different types of MSDs and various physical risk factors. This is much less the case for organizational and psychosocial risk factors. Several psychosocial risk factors are associated with an increased likelihood of workers reporting MSDs. The following risk factors are found to be significantly related to all three types of MSDs (backache, lower limb and upper limb) [10]:

- working under time pressure and deadlines;
- lack of work breaks;
- lack of social support received by colleagues, supervisors or management;
- high work demands and low work demands;
- poor job design, no task variation;
- job insecurity, temporary work and piecework: less skilled manual workers at the
- lower end of the labour market are most affected;
- low status work: low-paid, unskilled, paced and repetitive work.

These risk factors do not only lead to stress, but can increase the risk of MSDs because stress related changes in the body such as increased muscle tension could make workers more susceptible to MSDs. Psychosocial risk factors may affect workers' psychological response to work and workplace conditions or may change their behaviour [10], [33].

2.5. Types of Work Related Musculoskeletal Disorders

Most of the disorders, generically defined as musculoskeletal, result from aging, but often they are caused by incorrect movements and/or postures adopted in both work and daily life activities. It is important to recognize however that not all MSDs are caused by work, although work may provoke symptoms and the problem may prevent a person from working, or make it more difficult. Musculoskeletal and biomechanical overload disorders encompass a broad panorama of disorders which are found primarily in four body parts [19]:

- in the **wrist**, for example carpal tunnel syndrome, or in other words compression of the median nerve at the carpal tunnel, which is involved in gripping and dexterity; and tendinopathies of the extensor/flexor muscles of the fingers;
- in the **elbow**, for example diseases of the tendons of the external aspect of the elbow (tendinopathies of the lateral epicondyle muscles), which carry out gripping under strain; and ulnar nerve compression syndrome at the elbow;
- in the **shoulder**, for example diseases of the shoulder rotator cuff tendons (tendinopathies of the shoulder rotator cuff), caused in particular by movements and positions in which the arm is stretched out from the body;
- in the lower **back**, for example lumbar radicular pain (lower back pain that radiates into the lower limbs or predominantly radicular pain) caused by a herniated disc.

2.5.1. Back work-Related Musculoskeletal Disorders

Statistics indicate that back injuries or disorders are the most common body's disease [2], [19], [34]. Main cause of these injuries is the overexertion, but many of them are developed over a long time period due to a repetitive loading of the vertebral discs associated with unsuitable lifting methods [35]. Actually, a bad load lifting or manual material handling causes 27% of industrial back injuries. These disorders or injuries can be repetitive or chronic as result from years performing tasks. Normally, the worst injuries are the result of long term impact. Along the spine, the discs change of size, they are round, rubber-like pads filled with thick fluid, cushioning the impacts or the overloads. The accumulative forces along the back could compress the discs. This compression can break the pads of discs causing a spinal nerve pressure and producing acute back pain [35].

The most common alterations are:

- **Arthritic beaks** (osteoarthritis) are small bony bumps that form on the edge of the vertebra and can cause local pain. If they compress a nerve, they cause tingling and pain in the arms or legs such as: tingling in the hands in cervical arthrosis; lumbo-sciatica, or "sciatica" (inflammation of the sciatic nerve), in lumbar arthrosis.
- **Acute low back pain** is manifested by an acute pain, often temporarily immobilizing, caused by an immediate reaction of muscles and other structures of the back to incorrect movements or excessive effort. Usually the symptom appears within a few hours and should be considered as an injury if the cause is work-related.
- **Disc herniation** occurs when the central part of the intervertebral disc, called nucleus pulposus, crosses the fibrous ring that encloses it and exits the disc, compressing the nerve. It is often the consequence of overloading manual movements that can give rise to serious disturbances, including low back pain, which manifests itself with pain in the lumbar region radiating to the buttock and thigh.
- **The alterations of the curves of the column**: Kyphosis, Lordosis, Scoliosis. All these alterations do not derive directly from work activities but can be congenital or due to a lack of adequate physical activity. Such alterations, if present in significant form, can increase the chances of having work-related back problems.

Risk factors and work environment Many factors can contribute, individually or in association with others, to the occurrence of spinal pathologies. The main risks factors are correlated with the *manual handling of a load*. Manual handling of a load refers to the lifting or carrying of a load by one or more workers, including the actions of lifting, laying, pushing, pulling, carrying or moving a load which, due to their characteristics or unfavorable ergonomic conditions, involve risks of biomechanical overload pathologies, in particular of the back.

The following are the main risk elements to consider [2], [34], [36].

A. The characteristics of the load

  - is too heavy;
  - is bulky or difficult to grip;
  - is in unstable balance;
  - is placed in a position where it must be held or handled at some distance from the some distance from the torso or with a twist or tilt of the torso;

B. The physical effort required:

- is excessive;
- can only be performed with a twisting movement of the trunk;
- may involve an abrupt movement of the load;
- is performed with the body in an unstable position;
- involves high frequencies and/or prolonged lifting times.

C. Characteristics of the working environment:

- the free space, particularly vertical, is insufficient for the performance of the required activity (confined spaces) or the activity should be performed in a sitting or kneeling position;
- the floor is uneven, thus presenting tripping or slipping hazards for the worker;
- the workplace or environment does not allow the worker to handle loads manually at a safe height or in a good position;
- the floor or work surface has differences in level that require the load to be handled at different heights;
- the floor or support point is unstable;
- the temperature, humidity or ventilation is inadequate.

D. Activity-related demands:

- physical exertion is too frequent or too prolonged (e.g., static support of a load);
- insufficient breaks or recovery periods;
- excessively long lifting, lowering or carrying distances;
- a pace imposed by a process that cannot be modulated by the worker.

E. Individual risk factors:

- physical unfitness to perform the task in question, bearing in mind also that physical strength usually differs according to gender and age;
- Inadequate clothing, footwear or other personal effects worn by the worker;
- Insufficient or inadequate knowledge, education or training.

2.5.2. Work Related Upper Limb Musculoskeletal Disorders

Musculoskeletal disorders of the upper extremity primarily affect:

- the shoulder, which is extremely stressed in the course of upper limb movements;
- the elbow;
- the wrist, in which there is the carpal tunnel, carpal tunnel, a channel delimited by the bones of the carpus and the transverse ligament of the carpus, inside which the median nerve passes together with the flexor tendons of the fingers.
- the hand

The most common alterations are:

- **Shoulder:** scapulohumeral periarthritis. It is a disease that involves the shoulder joint. It initially presents with mild pain in the shoulder, often at night, then with difficulty in making certain movements of the arms and, over time, if not treated, can lead to almost total blockage of the joint (frozen shoulder).
- **Elbow:** epicondylitis and epithrocleitis. Epicondylitis, also known as "bending elbow", is an alteration of the lateral part of the elbow (epicondyle) and is characterized by localized pain, which increases with movement, and by a feeling of weakness in the arm in lifting even light weights. Epitrocleitis, or "golfer's elbow", less frequent, affects the medial part of the elbow (epitrochlea) and the symptom is pain localized at this level.
- **Wrist:** carpal tunnel syndrome (compression of the median nerve at the wrist). It is due to the compression of the median nerve as it passes through the carpal tunnel. It manifests itself with tingling and numbness in the first three fingers of the hand and part of the fourth finger which appear mainly in the morning and / or during the night; later, pain appears that also radiates to the forearm with loss of sensitivity in the fingers and hand strength.
- **Hand-wrist:** tendonitis. The predominant symptom of tendonitis is pain during movement. The tendon may appear swollen and in the most severe forms it may be impossible to move. In trigger finger, there is the formation of a lump in the tendon that causes a characteristic click accompanied by pain during flexion and extension movements of the affected finger.

Risk factors and work environment The main risk factors for the upper limbs and the complementary risk factors are:

- prolonged duration of the work task;
- frequency and / or repetitiveness of work actions;
- high force used;
- incongruous posture;
- insufficient recovery times;
- high precision;
- localized compressions of the anatomical structures;
- use of incongruous individual devices (gloves, shoes, etc.);
- use of non-ergonomic work equipment;
- cold exposure;
- use of vibrating tools;
- handling slippery objects.

2.5.3. Work Related Lower Limb Musculoskeletal Disorders

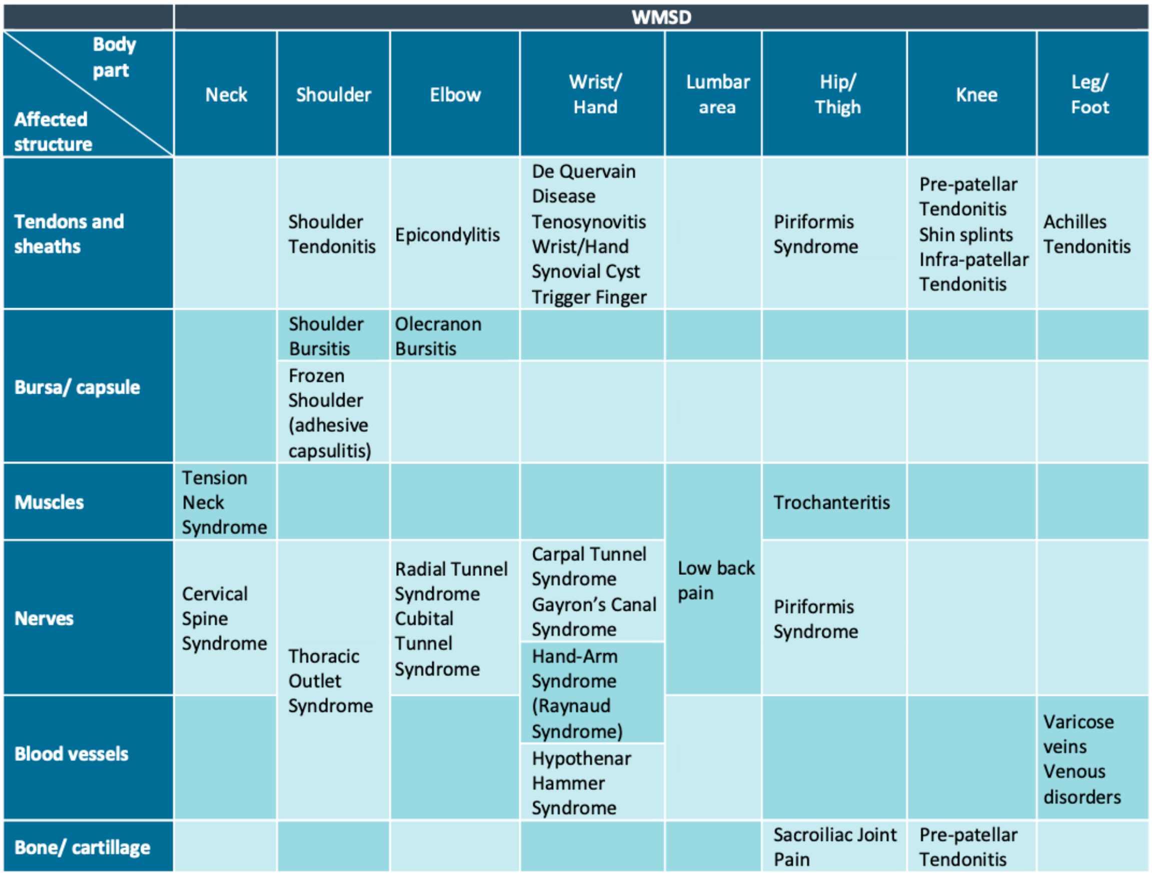
The most frequent alterations of the lower limbs connected with work concern the knee and the foot.

- **Injuries of the meniscus:** the most frequent symptom is a pain localized in correspondence of the meniscus that is accentuated during the flexion movements of the knee. In some cases there may be swelling of the joint.
- **Pre-patellar bursitis:** correlates with activities that take place while kneeling. The most common symptom is swelling above the patella, often associated with reduced mobility of the joint, redness and local heat. The pain increases during kneeling, movement and palpation of the joint.
- **Knee tendinopathy:** it is characterized by pain in the lower part (tendonitis of the patellar) or high (quadriceps tendonitis) of the patella which becomes accentuated under exertion, particularly when jumping and kneeling. The pain increases if the knee is palpated. Sometimes there is swelling, warmth and local redness.

- **Plantar talalgia:** it is a painful condition that affects the heel and can arise in subjects forced into prolonged upright posture or due to exposure to repeated trauma.
- **Achilles tendonitis:** inflammation of the Achilles tendon resulting in pain in the back of the ankle and heel.
- **Tarsal tunnel syndrome:** syndrome due to a compression of the posterior tibial nerve that manifests itself with tingling in the sole of the foot and pain.

Table 2.3 synthesizes the most relevant MSDs described above and groups them by body part and anatomical structure affected.

Table 2.3: Most relevant WMSD by body part and affected anatomical structure adapted from [35]



	WMSD							
Body part Affected structure	Neck	Shoulder	Elbow	Wrist/ Hand	Lumbar area	Hip/ Thigh	Knee	Leg/ Foot
Tendons and sheaths		Shoulder Tendonitis	Epicondylitis	De Quervain Disease Tenosynovitis Wrist/Hand Synovial Cyst Trigger Finger		Piriformis Syndrome	Pre-patellar Tendonitis Shin splints Infra-patellar Tendonitis	Achilles Tendonitis
Bursa/ capsule		Shoulder Bursitis	Olecranon Bursitis					
		Frozen Shoulder (adhesive capsulitis)						
Muscles	Tension Neck Syndrome				Low back pain	Trochanteritis		
Nerves	Cervical Spine Syndrome	Thoracic Outlet Syndrome	Radial Tunnel Syndrome Cubital Tunnel Syndrome	Carpal Tunnel Syndrome Gayron's Canal Syndrome Hand-Arm Syndrome (Raynaud Syndrome)		Piriformis Syndrome		
Blood vessels				Hypothenar Hammer Syndrome				Varicose veins Venous disorders
Bone/ cartilage						Sacroiliac Joint Pain	Pre-patellar Tendonitis	

3 | State of the Art

As widely discussed in chapter 2 the MSDs represent the major contribution for occupational diseases, namely in Europe. These disorders result from working conditions that expose workers to risk factors like high loads, repetitive motions, static loading (lifting) and poor posture, among other reasons, all of which are major risk factors. In the last years, more attention has been drawn to this issue as it is one of the main concerns and research priorities of the European Agency, not only due to the health effects on individual workers but also because of the economic costs involved such as insurance, medical and administrative costs, sick leave costs, early retirements, and the reduction of the productivity levels. This chapter aims at presenting the current methods developed and used for WR-MSDs assessment and prevention, highlighting their advantages and disadvantages. Nowadays, three major methods can be identified: self-reports, observational methods, and instrument based. A review of the current methodologies will be discussed, focusing on the instrument based methods and in particular on the wearable devices developed for ergonomic purposes. This chapter provides also information about the European Directives, the minimum requirements and principles of prevention and risk assessment at work.

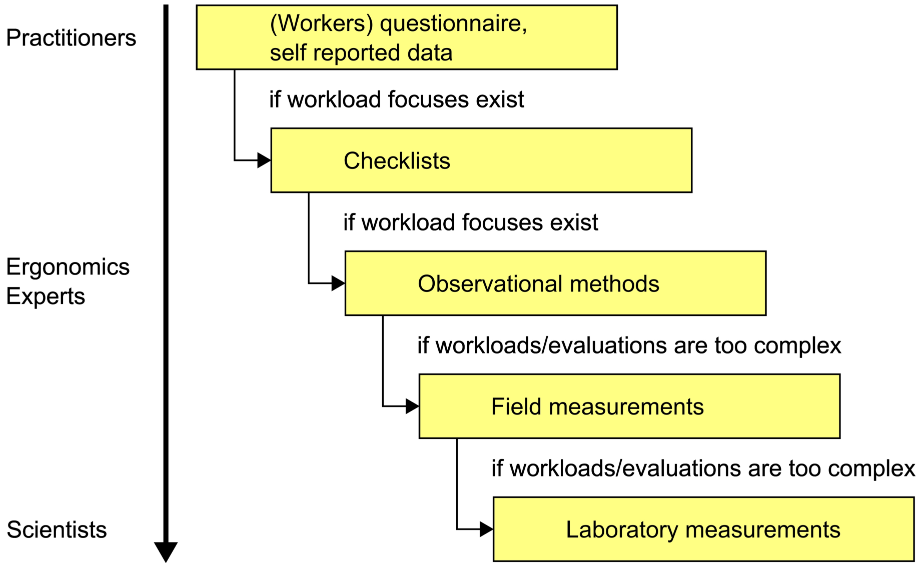
3.1. WR-MSDs Risk Assessment Methods: Current Status

The measurement of workers' exposure to the factors that may contribute to the development of WR-MSDs has been of vital importance to both epidemiologists and ergonomists conducting research studies. There has also been parallel interest from ergonomics practitioners, occupational health physicians, employers, employee representatives and regulating authorities in measuring exposure to known risk factors as the basis for programs of risk prevention and reduction. It is now clear that these programs should be founded upon ergonomics principles and should incorporate the holistic assessment of all elements of the work system so that optimal solutions can be achieved. This range of generic issues should be considered, such as task design, worker/equipment interface, training needs, work organization and legal requirements [3], [37]. The literature presents several methods for risk exposure assessment and to evaluate the need for ergonomic intervention. These tools can be classified as self-reports, observational methods and direct methods [3].

The choice of method will depend upon the nature of the investigation and the purpose for which the data will be used; these will determine the level of accuracy and precision that is required [3], [38]. Some methods are suitable for use only by highly skilled investigators and require extensive use of resources. Other techniques that enable more general, observation-based assessments to be made are more suited to the needs of occupational safety and health practitioners or those from related professions, who have limited time and resources at their disposal for making assessments. Assessing exposure to risk factors for WMSDs is an essential stage in the management and prevention of WMSDs, when it may form part of an overall risk assessment program that will be discussed in Section 3.2.

Table 3.1 shows the basic categories of methods for recording and assessment of physical risk exposure at the workplace with their potential user groups [38], [39]. The top category (Level 1) covers questionnaires and self reported data. In this category workers have to estimate retrospectively the occurrence and frequency of their daily amount of physical risk exposure. Epidemiological studies on work-related MSDs often use self-reported data for exposure assessment.

Table 3.1: Basic categories of methods for recording and assessment of physical risk exposure at the workplace and potential user groups [39].



These methods are known as inaccurate workload assessments as the workers' ability to estimate their physical risk exposure is limited and workers that already suffer from MSDs tend to overestimate their exposure. In the next category (Level 2) checklists are used to identify workload focused at the workplace. Normally checklists contain limiting values for the assessment of specific physical workload types. If these limiting values are exceeded, workload focuses can be identified. Checklists are often used in combination with medical check-ups. If a physical risk factor occurs, such as the lifting and carrying of loads, it is advisable to employ more specific observational methods (Level 3) in order to assess the associated risk factors more precisely. Observational methods are subject to the usual limitations of this category. The drawback of these methods is that they only roughly classify workload categories and often do not adequately reflect the complexity of work processes [40]. Therefore some applications necessitate the performance of measurements of physical workloads directly at the workplace (field measurements, Level 4). The field measurements offer an even higher degree of differentiation in relation to the identification of physical stress compared to the screening methods. Field measurements should be carried out if special stress situations (high risk, complex stress) are expected. The limitations of measuring methods at the workplace include limitations in terms of the measurement accuracy characteristic of field measurements in real working conditions. This is where laboratory measurements (Level 5) in which work processes are replicated under standardized experimental conditions yield the most precise data on the physical workload situation [38].

3.1.1. Self-reports

Self-reports from workers can be used to collect data on workplace exposure to both physical and psychosocial factors by using methods that include worker diaries, interviews and questionnaires. Generally, data collection has been by written records, but more recent innovations include the self-evaluation of video films of work tasks [41] or the use of web-based questionnaires [42]. These methods have the apparent advantages of being straightforward to use, applicable to a wide range of working situations and appropriate for surveying large numbers of subjects at comparatively low cost. Estimations of exposure for extended periods can be determined and for longer duration than may be realistically expected by making observations at the workplace. Large samples sizes are normally required to ensure that the data gathered are representative of the occupational groups being investigated. The subsequent analysis costs can be high and appropriate skills are necessary to interpret the findings accurately [3]. A major problem with these methods is that worker perceptions of exposure have been found to be imprecise and unreliable. For example, having severe low back or neck pain was found to increase the probability of workers reporting higher durations or frequencies of physical load in comparison with those workers from the same occupational groups who were pain free [43], [44]. Further, difficulties with self-reports may arise from varying levels of worker literacy, comprehension or question interpretation. Although quantification of the absolute level of exposure is doubtful using these methods, occupational groups at comparatively higher risk can be identified for more detailed analysis using other methods. Their levels of reliability and validity are reportedly too low for use as the basis for ergonomics intervention [3].

3.1.2. Observational Techniques

Observational methods are probably the most often used approach to evaluate physical workload in order to identify hazards at work, monitor the effects of ergonomic changes, and conduct research on these issues. The number of available methods is large, but no single one is suitable for all purposes - different approaches are needed for different goals [45]. Observational methods aim to detect workplace risk exposure by observation made by ergonomics experts and can be subdivided into simpler and advanced.

Simpler Observational Techniques The simpler ones, also called *pen and paper* methods, are performed on job site by an ergonomic expert. The most common observational methods used for upper body evaluation are Rapid Upper Limb Assessment (RULA), Ovako Working Posture Analysing System (OWAS), Occupational Repetitive Actions (OCRA), Rapid Entire Body Assessment (REBA) and the NIOSH lifting equation, other examples are given in Table 3.2.

These methods evaluate different parameters, such as posture, frequency, duration, force, recovery time, among others. Simpler observational methods have the advantages of being inexpensive and practical for use in a wide range of workplaces where using other methods of observing workers would be difficult. The disadvantages of these techniques are the dependency on the analyst expertise and the lack in precision and objectiveness [40]. These enable overall indices or scores for combinations of exposure factors to be determined with the aim of prescribing acceptable exposure limits for workers. The epidemiological data upon which these scoring systems are based is limited particularly with respect to how different factors should be weighted, or interactions between factors should be quantified. The scoring systems are therefore largely hypothetical [3]. Due to differences in methods and diversity in user needs, the selection of an appropriate tool can be challenging. The selection of a method should be based on [45]:

- the objectives of its use;

Table 3.2: Examples of simpler observational methods [3].

Reference	Technique	Main features	Function
[46]	EAWS	provide an overall risk evaluation that includes every biomechanical risk.	Entire body assessment.
[47]	OWAS	Time sampling for body postures and force	Whole body posture recording and analysis.
[5]	NIOSH	Measurement of posture related to biomechanical load for manual handling.	Identification of risk factors and assessment.
[48]	Snook & Ciriello	Determine the maximum acceptable force that a worker is prepared to exert to perform different repetitive movements.	Assessment of risk for back and wrist.
[6]	Strain Index	Combined index of six exposure factors for work tasks.	Assessment of risk for distal upper extremity disorders.
[4]	RULA	Categorization of body postures and force, with action levels for assessment.	Upper body and limb assessment.
[49]	REBA	Categorization of body postures and force, with action levels for assessment.	Entire body assessment for dynamic tasks.
[7]	OCRA checklist	Measures for body posture and force for repetitive tasks.	Integrated assessment scores for various types of jobs.

- the characteristics of the work to be assessed;
- the individuals who will use the method;
- the resources available for collecting and analyzing data.

Advanced Observational Techniques A range of video-based observational techniques has been developed for the assessment of highly dynamic activities; some examples are given in Table 3.3. Each of these methods record data either on videotape or by computer that are subsequently analyzed objectively using dedicated software. The worker's postural variations are recorded in real time for a representative work period, and several joint segments may be analyzed simultaneously. Several dimensions may be determined, such as distance of movement, angular changes, velocities and accelerations. The analysis may include the use of biomechanical models that represent the human body as a set of articulated links in a kinetic chain and use anthropometric, postural, and hand-load data to calculate intersegmental moments and forces. These range in complexity from two dimensional static models to three dimensional dynamic models. The costs of the above-mentioned systems can be substantial, and they require extensive technical support from highly trained staff for effective operation. They can be time consuming to use in practice and have been found more suitable for use in recording and analyzing simulated tasks, rather than for conducting practical assessments in the workplace [3]. The following list includes some of the most used methods to evaluate physical workload in order to identify hazards at work.

EAWS: Ergonomic Assessment Worksheet

Stated purpose: EAWS [46] is an ergonomic 1st level tool for screening the risk due to biomechanical overload, developed to provide an overall risk evaluation that includes every biomechanical risk to which an operator may be exposed during a working task. It's therefore a holistic system (full coverage of all risk areas) and it provides detailed results in four sections: Body Postures, Action Forces, Manual Materials Handling, Upper Limbs.

Description: the EAWS consists of four sections for the evaluation of working postures and movements with low additional physical efforts, action forces of the whole body or hand-finger system, manual materials handling and repetitive loads of the upper limbs. Sections one to three base their evaluation on physiological and biomechanical criteria; section four is based on medical and epidemiological data. With respect to the different evaluation approaches the results of sections one to three are combined to a whole body exposure, whereas section four indicates the load situation of the upper limbs.

OWAS: Ovaka Working Posture Analysing System

Stated purpose: OWAS [57] is a semi-quantitative analysis method for identifying and assessing stressful work postures; determining how urgently corrective measures are required to the job by a classification into four categories of action (from "no action" to "immediate corrective action").

Body region assessed: Back, upper and lower limbs.

Table 3.3: Examples of advanced observational methods [3]

Reference	Technique	Main features	Function
[50]	Video analysis	Time sampling of video films and computerized data acquisition for both posture and force.	Posture assessment.
[51]	ROTA	Computerized real time or time sampling recording and analysis of activity and posture.	Assessment of dynamic and static tasks.
[52]	TRAC	Computerized time sampling recording and analysis of activity and posture.	Assessment of dynamic and static tasks.
[53]	HARBO	Computerized real time recording of activity and posture.	Long duration observation of various types of jobs.
[54]	PEO	Computerized real time recording of posture and activity.	Various tasks performed during period of job.
[55]	PATH	Computerized work sampling of posture and activity.	Non-repetitive work.
[40]	SIMI Motion	Video-based analysis of three dimensional movement.	Assessment of dynamic movement of upper body and limbs.
[56]	Biomechanical models	Linked segmental representation of the human body.	Estimation of internal exposures during task performance.

Description: It is a three-stage method:

1. Video recording of the job.
2. Observation of the videotape at regular intervals identifying the postures of back, arms and legs.
3. Classification into four action categories:
    - Action Level 1: acceptable conditions; no changes needed;
    - Action Level 2: some harmful effect; changes to be made in the future;
    - Action Level 3: distinctly harmful effect; changes to be made as soon as possible;

- Action Level 4: extremely harmful effect; immediate solutions should be found.

What makes this method different is that it involves studying working conditions over time, identifying the frequency of postures and efforts over the sample. By focusing on variations, it is more approximate in its assessment of postures. This approach has been used by other researchers focusing on specific body regions [58].

NIOSH Equation

The National Institute of Occupational Safety and Health (NIOSH) [5] has developed many useful tools and documents to aid industries in developing an ergonomics program. A commonly known tool that NIOSH developed is the NIOSH Lifting Equation, which is used to determine the risk of a low back injury while performing lifting tasks.

Stated purpose: the aim is to assist safety and health practitioners to evaluate, prevent or reduce the occurrence of low back pain and disability for workers engaged in repetitive load lifting or lowering tasks in the sagittal plane of movement. The method is used to determine the recommended weight limit of a load based on the lifting characteristics and to propose preventive measures [5].

Body region assessed: Back.

Description: The method applies only to load lifting and lowering operations. It computes the "Recommended Weight Limit" (RWL) based on lifting or lowering task conditions: distance of the load from the front of the body, height of the load, vertical travel distance, body twist, quality of coupling (grip), duration and frequency of the task. The "Lifting Index" (LI) is computed as the ratio between the weight of the load lifted and the recommended weight limit. Depending on the value of this index, the risk:

- is negligible (< 1);
- exists and the situation requires improving (1-3); or
- is unacceptable (> 3).

A Composite Lifting Index (CLI) can be calculated for frequent manual handling tasks with varying distances, heights, frequencies, etc., Niosh method is a well-documented, scientifically robust method tested in numerous laboratory studies. It was designed for risk prediction. The multiplier factors for the different components enable the factors that most limit the recommended load weight, and are therefore responsible for the increased risk of lower back injuries, to be identified [5], [58].

Snook & Ciriello Tables

Stated purpose: The Snook and Ciriello Tables [59], called psychophysical tables, determine the maximum acceptable force that a worker is prepared to exert to perform different repetitive movements.

Body regions covered: mainly back and wrists.

Dscription: the psychophysical response is the maximum exertion that a worker is willing to make under different conditions and over a certain period of time, working as hard as possible but without experiencing more fatigue, weakness or breathlessness than normal. Tables give acceptable values for 10, 25, 50, 75 or 90% of men and women performing four types of activities:

- Lifting/lowering: maximum acceptable lifting and lowering weights according to the width of the object, load height at start, lift/lower distance and task frequency.
- Pull/push: maximum force needed to start and keep the load moving according to the vertical distance between floor level and grasp height, and the carrying distance.
- Carrying of loads: maximum acceptable weight according to hand height from floor level, carrying distance and task frequency.
- Wrist flexion and extension (women only): maximum torques according to working time and maximum forces of grip and pinch with the wrist in flexion (downward or inward movement of the wrist) or extension (upward movement of the wrist - palm facing outward).

As for the NIOSH equation presented previously, the quantifying process should preferably be accompanied by a discussion with the workers to identify preventive measures and improvements.

RULA: Rapid Upper Limb Assessment

Stated purpose: RULA [4] aims to make a quick and easy assessment of working conditions in which MSDs have been reported. The method was developed to screen workers at risk, identify the muscular effort associated with different risk factors which may contribute to muscle fatigue, and possibly to be incorporated into a general ergonomic assessment method.

Body region covered: Shoulders, elbows, wrists, neck, trunk.

Description: The figure 3.1 summarises the method. The body is divided into two groups with three body parts per group (A: shoulders, elbows, wrists and B: neck, trunk, legs). A posture score is assigned to each body part from tables accompanied by diagrams. These scores are added up for each group. A static muscle work score and a force score taking into account the repetition of motions are determined for each group and combined with the posture scores. A final table gives a single grand score from both groups. Four action levels are defined from the final score:

- Action level 1: low risk; posture acceptable.
- Action level 2: further investigation is needed and changes may be required.
- Action level 3: further investigation is needed and changes are required soon.
- Action level 4: further investigation is needed and changes are required immediately.

Figure 3.1: RULA method [4]

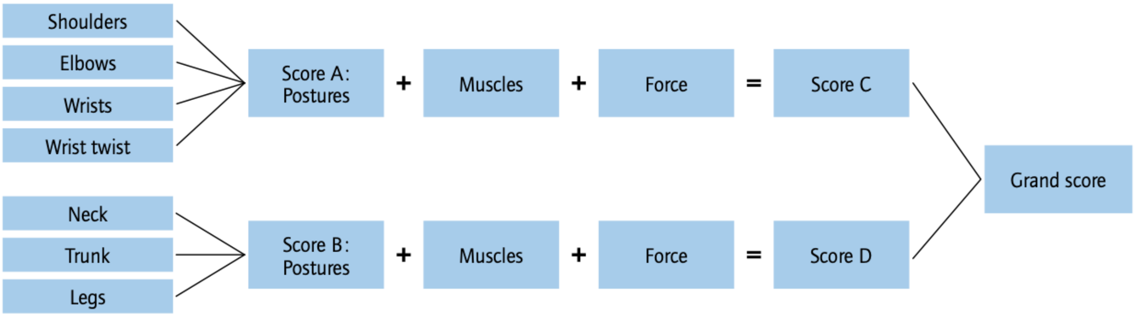
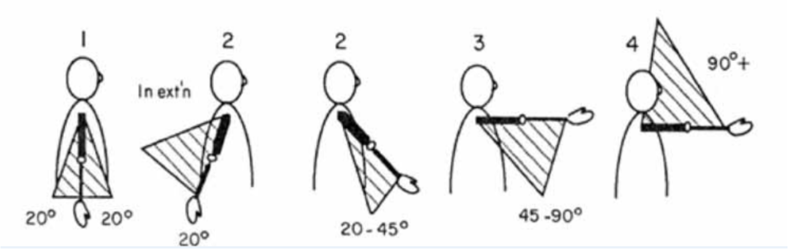


Figure 3.2: Action levels of RULA method [4].



The method was developed by researchers and has been used by others for epidemiological research purposes. The final score determines the overall level of risk of MSDs, but does not inquire into causes or lead to solutions for improvements. The hours or days of analysis required to determine the representative work period, make one or more video recordings, and calculate the scores lead to what is arguably an outcome (further long, medium or short term investigation required) [58].

REBA: Rapid Entire Body Assessment

Stated purpose: REBA is a tool used to evaluate the risk of musculoskeletal disorders associated with specific tasks within a job. It is a whole-body screening tool that follows a systematic procedure to assess biomechanical and postural loading on the body [60].

Body region assessed: entire body.

Description: it is composed by different steps [49]:

1. Identify a job. You can identify a job to assess by reviewing where past injuries have occurred, where operator complaints have been reported or where quality issues have been a concern.
2. Define and understand the tasks within the job. Interview the operator to gain an understanding of the main job tasks, the task demands, and what the operator perceives to be the most difficult component(s) of the job.
3. Identify the tasks within the job you intuitively believe have the highest MSD risk. From personal observation and the information gathered from the operator interview, select the "worst" parts of the task to assess. This should be based on the most awkward postures present, the highest force exerted, awkward postures held for an extended period of time, or awkward postures that are repeated multiple times.
4. Complete the REBA data collection form. The REBA evaluates the whole body, including the upper arm, lower arm, wrist, neck, back and legs. From the photo, compare the position or postures of each body segment to those outlined on the REBA data collection form. The REBA provides a score for each body segment based on these postures. Note that the upper limbs must be analyzed separately (right versus left upper limb) if they are performing different actions.
5. Determine the REBA score. The REBA provides a single final score based on the posture evaluated, force requirements, type of movement, frequency of movement and coupling observed within the task. This single value, ranging from 1 to 15, represents the work-related MSD risk to the operator. It also provides a level of urgency for engineering changes to the workstation. A score greater or equal to 8 indicates that there is high MSD risk to the workers completing the task and that engineering controls are recommended.

OCRA index: Occupational Repetitive Actions Index

Stated purpose: The objective is to classify work situations according to their exposure to MSDs and to calculate the amount of exposure to tasks involving repetitive movements of the upper limbs [7].

Body region assessed: upper limbs.

Description: OCRA index is computed as the ratio between the number of actual technical actions (ATA) performed by the worker during the work cycle and the number of recommended technical actions (RTA) for each upper limb. The technical action is the elementary manual action required to complete an operation (i.e. holding, turning, pushing, etc.). The number of recommended technical actions is obtained as the production of several weights that depend on repetitiveness of tasks, i.e., frequency factor, postures, exerted force, work cycle and recovery period, as reported in Table 3.4 [61]. Finally, the OCRA index can fall into different five risk areas [7]. When OCRA values fall into the highest risk range, improve working conditions by redesigning tasks and workplaces, activate the health surveillance and enhance the worker training are the main suggested actions to undertake.

Table 3.4: Table of the parameters considered in the OCRA index [61].

Parameter	**Description**
Fom	The parameter refers to the force applied. It can be calculated as a percentage of maximum voluntary contraction (MVC) or using the CR-10 Borg scale.
Pom	The parameter refers to awkward or uncomfortable postures. It is calculated taking into consideration the angles and the percentage of the cycle time in which the uncomfortable posture is present. The lowest Pom must be chosen (corresponding to the worst condition).
Rem	The parameter refers to the high repetition of the same movements.
Adm	The parameter refers to the presence of additional factors. I.e.: vibration tools, gloves, gestures implying countershock, exposure to cold surfaces...
Rcm	The parameter refers to the presence of a recovery period: breaks, visual control tasks, periods within the cycle that leave muscle totally at rest consecutively for at least 10s, almost every few minutes.
Dum	The parameter refers to the total time of repetitive tasks during the shift (min).

Assessment is a three-stage process [7], [58]:

1. Determining the frequency of technical actions per minute and calculating the total number of technical actions actually carried out during the work shift, for each upper limb.
2. Calculating the total number of recommended technical actions carried out during the work shift according to the frequency of awkward forces, postures or move-

ments, repetitions of the same movements, the presence of additional factors (cold, gloves, vibration, sudden movements, etc.), recovery periods and the daily duration of repetitive tasks. This stage requires many calculations to be performed, including the percentage of time that the shoulder is in flexion or abduction to 80° or more, the wrist is in radial or ulnar deviation to $\geq 20°$, gripping is forceful with a narrow span (≥ 2 cm) and so on.

3. Calculating the OCRA risk index = ATA / RTA.

The OCRA index is widely recognized as the most complete and sophisticated quantifying methods which claims to achieve precision by accumulating assessments of details; it is also the most widespread for assessing biomechanical risk related to repetitive tasks performed by upper limbs.

OCRA Checklist

Stated purpose: realizing that the OCRA index is quite complex and time-consuming to use, the authors developed a simpler checklist for "initial screening" of jobs involving repetitive tasks, while the OCRA index would be useful for the redesign and analysis of such jobs. The authors say that the checklist is not a substitute for assessing exposure by the OCRA index, since this is more accurate. However, they do say that the checklist is essential during the first phase of risk assessment for initial "risk mapping" [7].

Body regions assessed: upper limbs, but mostly the hands.

Description: the checklist allows an OCRA score to be calculated by first adding up partial scores from the frequency of technical actions, forces, recovery periods, shoulder-elbow-wrist-hand, positions, repetitiveness and the presence of additional factors (cold, gloves, etc.). The final score is obtained by multiplying these by a work duration factor. OCRA score = (Frequency + Force + Recovery + Position + Repetitiveness + Other) x Work duration. The scores are interpreted using the table 3.5. The OCRA Checklist can be visualized at [62].

Table 3.5: OCRA scores interpretation [58]

OCRA score	OCRA index	Colour	Risk
< 7.5	2.2	🟢	Acceptable
7.6 – 11	2.3 – 3.5	🟡	Limited risk
11.1 – 14	3.6 – 4.5	🟠	Low risk
14.1 – 22.5	4.6 – 9	🔴	Medium risk
> 22.5	> 9	🟣	High risk

3.1.3. Direct Methods

Despite the self-report and observational methods, more quantitative, objective, and accurate data is required. Direct or instrument-based methods can acquire, in real time, the ergonomic level risk. The use of modern measuring devices, placed on the user's body, could lead to objective and more accurate results, reducing the time needed for an ergonomic evaluation and allow the assessment of dynamic tasks. Some of the direct measurements methods provide lightweight portable devices for the measurement of body joint angles together with corresponding system for computerized data analysis [63].Others have been further developed for the simultaneous recording [64], myoelectrical activity recording [65] and muscle fatigue, electronic exoskeleton such a Lumbar Motion Monitor [66], or whole-day ambulatory monitoring of occupational work based on accelerometer sensors [67], [68]. In addition, another type of direct measurement, has been developed for collecting posture data using optical markers, optical marker-less, and inertial markers. These technologies provide a digitalization of the subjects' motion, a promising technique for posture evaluation that has been exploited by researchers in the last years [69]. These advanced and instrument-based methods will be deeply discussed in section 3.3.

3.2. Regulatory Framework for MSD Prevention

Legal obligations concerning the prevention of musculoskeletal disorders are defined by specific directives issued by the European Union in order to ensure in member countries the improvement of the safety and health of workers at work. European Directives set out minimum requirements and fundamental principles as well as the responsibilities of employers and employees. A series of European guidelines aims to facilitate the implementation of European directives as well as European standards which are adopted by European standardization organizations. The Framework Directive 89/391 EEC [70], with its wide scope of application, and further directives focusing on specific aspects of safety and health at work are the fundamentals of European safety and health legislation. Member States are free to adopt stricter rules for the protection of workers when transposing EU directives into national law. Therefore, legislative requirements in the field of safety and health at work can vary across EU Member States. In Italy, the transposition of Directive 89/391 [70] was made with the Legislative Decree 626/94 [71] and subsequent to the current Legislative Decree 81/08 [36]. Legislative Decree 81/08, coordinated with Legislative Decree 106/2009, provides a real "Code of Health and Safety at Work". Totally consistent with current EU and international regulations on safety in the workplace, it constitutes the legal basis of the strategy to combat the phenomenon of accidents and that of occupational diseases.

3.2.1. Standards and Tools

The alarming scenario which depicts the actual health condition of European workers requires a specific and tailored set of normatives and standards to minimize the risk of musculoskeletal disorders during manual manufacturing and assembly activities. The Framework Directive (89/391/EEC) [70] obliges employers to implement preventive measures to encourage improvements in the safety and health of workers. The obligation in the Framework Directive to assess risks covers all ergonomic conditions and risks, including repetitive work, pushing and pulling, work positions and movements, and manual handling. Two are the most relevant and widespread norms which tackle this problem, namely the international standard ISO 11228 [72] and the European one EN 1005 [73]. In particular, the different sections of these norms focus on the analysis of different manual handling activities relevant to establish ergonomic recommendations and ensure the operator health. The first section of ISO 11228 (ISO 11228-1) [72] and the second section of EN 1005 (EN 1005-2) [74] aim to define specific limits for repetitive and non-repetitive manual lifting and carrying of objects of 3 kg or more of weight considering several aspects of the performed task as its intensity, frequency and duration. ISO 11228-2 [74] and EN 1005-3 [75] focus their attention on the pushing and pulling of objects analyzing its impact on the entire musculoskeletal architecture to identify potential hazards in relation to the object weight and the tools used. Furthermore, ISO 11228-3 [76] and EN 1005-5 [77] evaluate the tasks distinguished by handling low loads at high frequency (loads $<$ 3 kg). Finally, ISO 11226 [78] , which is the extension of ISO 11228, and EN 1005-4 [79] are the guidelines adopted to assess the working postures hold by a worker during a manufacturing or an assembly activity.

Considering the analyzed normative and standard framework, the following list correlates the assessment methods suggested by the guidelines (discussed in Section 3.1.2) in relation to the working tasks with the main risk factors for WR-MSD (analyzed in Section 2.4).

- Lifting and carrying tasks are traditionally assessed through the NIOSH equation [5]. This method determines the recommended load weight limit for human lifting operations considering biomechanical, physiological and psychophysical aspects. The first aspect deals with the maximum compression force on the L5/S1 vertebral segment of spine, the second aspect assesses the maximum energy expenditure during lifting operation whereas the latter considers the maximum acceptable lifted weight for male and female workers. Both ISO 11228-1 and EN 1005-2 standards are based on the NIOSH equation.

- Pushing and pulling activities along with force limit considerations are assessed by Snook and Ciriello [59]. The authors estimate the force limits for pushing and pulling activities for male and female operators considering the task frequency and duration along with the pushing distance and height as well as the handled object size.

- The manual handling of low loads at high frequency is carefully analyzed by Occhipinti [7] . In the publication, an undex is proposed that assesses the exposure to repetitive movements of the upper limbs for manual activities. The developed index, named OCRA (Occupational Repetitive Actions) limits the number of tasks which can be performed by an operator during a shift considering the force exerted and the duration of each repetitive task. Then OCRA index is exploited by both ISO 11228-3 [76] and EN 1005-5 [77] for the development of their guidelines and recommendations. Similarly to OCRA, the Strain Index [6] estimates the risk of distal upper extremity disorders analyzing different features of a performed task, namely intensity, duration and speed of exertion as well as the number of exertion per minute, the wrist movement and the duration per shift.

- Finally, the operator postures are carefully assessed by three indices. Both OWAS, RULA and REBA analyze the working posture of an operator evaluating the position of the different body parts and the angle of several skeleton joints. However, the OWAS index approximatively estimates the body posture. RULA carefully assesses the upper limbs (wrists included) but it poorly estimates the posture of lower limbs, the legs in particular. Finally, REBA index is distinguished by the advantages of RULA along with a proper and thorough evaluation of lower limbs posture.

The Table 3.6 presents the relation between the manual material activity, the ISO and EN Standards as well the presented Ergonomic Assessment Tools.

Table 3.6: International and European standards for the assessment of manual handling activities.

	STANDARDS		**TOOLS**	
Risk Areas	**EN**	**ISO**	**Second Level**	**First Level**
Body posture	1005-4	11226	OWAS, RULA, REBA	EAWS
Lifting and carrying	1005-2	11228-1	NIOSH	EAWS
Pushing and Pulling	1005-3	11228-2	Snook & Ciriello	EAWS
Low loads at high frequency	1005-5	11228-3	OCRA, STRAIN INDEX	EAWS

3.2.2. Manual Handling of Low Loads at High Frequencies

For the purpose of this work we focus on the manual handling of low loads at high frequency tasks and in this section will be explained the step-by-step approach and available validated risk estimation tools, in accordance with international standards, to assess this the associated risk factors more precisely to this type of task. The manual handling of low loads at high frequency weighing less than 3 kg is a work task that is classified as repetitive task and the ergonomic recommendations are established by the technical standard ISO 11228-3 [76]. For the two-handed lifting and carrying of objects weighing more than 3 kg the standard to be applied is the technical standard ISO 11228-1 which provides a step-by-step guide to risk assess the lifting and carrying of loads and specifying limitations to the activity. ISO 11228 and ISO 11226 are independent with respect to data and methods, users may need guidance to select or use the rules in their specific application. The technical report ISO/TR 12295 [80], *"Ergonomics - Application document for international standards on manual handling (ISO 11228-1, ISO 11228-2 and ISO 11228-3) and evaluation of static working postures (ISO 11226)"* serves as an application guide to provide information on the choice and use of the ergonomic standards depending on the risks specific present in the company and is to be considered as application of the Framework Directive. It is applied in the risk assessment phase, but also in the design of activities involving the manual handling of loads or the assumption of static work postures, which can cause, over time, the onset of biomechanical overload pathologies. The TR [80] present a risk assessment method based on 3 steps:

1. First step: Key Questions

   The employer first of all checks whether activities are carried out in his company that may involve functional overload of the upper limbs. The key enter question of TR 12295 is:"Are there one or more repetitive upper limb tasks with a total duration of 1 hour or more in the shift?". Only if the answer is affirmative proceed with the 2nd step.

2. Second step: Quick Assessment

   The quick assessment consists of a quick check of the presence of potential risk conditions by simply answering predefined YES / NO questions. The technical report in this step aims to identify, without the need for calculations, the presence of the following three conditions:

   a. condition of "no risk" or "certainly acceptable risk", in which the evaluation process could immediately end without further action (other than to monitor the evolution of the business over time);

b. “certainly unacceptable” risk condition, in which a redesign of the post or work process is a priority (and in which an analytical assessment would be, in most cases, merely superfluous);

c. a risk condition comprised between the two conditions set out above (a. and b.), in which it is necessary to carry out a precise estimate or assessment using the analytical methods established by the above-mentioned ISO standards.

3. Third step: Analytical Risk Assessment

   For the purposes of estimating and subsequently assessing the risk determined by activities involving repeated movements of the upper limbs, the standard provides for an approach according to successive steps: an initial recognition of the dangers, which, if they exist, is followed by a first screening (method 1, consisting of a specific checklist) aimed at describing the activity and estimating the risk. The check list is divided into 5 successive steps, relating to the main risk factors (repetitiveness, application of force, incongruous movements and postures, insufficient recovery periods and complementary risk elements that may be present). The questions are structured in such a way that the possible answers fall into three bands, characterized by the colors green (negligible risk), yellow (possible risk) and red (high risk). If all the answers provided fall within the green band, the risk that characterizes the task is to be considered negligible and it will be necessary to periodically repeat the assessment. On the contrary, the presence of one or more responses belonging to the yellow or red band highlight, for the analyzed task, conditions of possible or high risk. In these cases it is necessary to deepen the investigation through a detailed analysis of the individual factors that characterize the activity in question. For this purpose, the ISO 11228-3 standard reports a list of evaluation protocols: among these, priority is given to the OCRA method, which allows the calculation of an index that takes into account various risk factors; subordinately to the above method, the Strain index protocol can be adopted, which however are applicable, with various limitations.

3.3. Technologies for Biomechanical Risk Assessment at Work

With the impact of novel electronic components, instrument-based methods for biomechanical risk assessment at work are becoming a trend and are more frequently used by experts. These methods range from simple, hand-held devices for the measurement of the range of joint motion to electronic goniometers that provide continuous recordings of the movement across joints during the performance of a task [3]. The existing systems for direct assessment of the human body posture can be categorized into:

1. **Goniometric-based**, such as the Lumbar Motion Monitor (LMM), a tri-axial electronic goniometer that measures of the displacement angle the thoracolumbar region in relation to the pelvis [66].

Figure 3.3: the industrial Lumbar Motion Monitor (LMM). Photo courtesy of Biodynamic Solutions, Inc.

2. **Sonic-based**, which use ultrasonic waves and are constituted by transmitters and receivers. Once the sound propagation on body tissue is constant, the distance between both sensors can be calculated and, therefore, measured the spine flexion [81]. An example is the system developed by [81], which integrate four pairs of ultrasound emitters and receivers with an inclinometer, a device that measures angles in relation to the gravity line, for the evaluation of trunk inclination and spine curvature. However, these systems present some drawback such as sampling rate, since distance measuring depends on the velocity of the sound in the body tissue. Also, the thickness of the subcutaneous fat and air noise and properties (e.g. temperature, air density) can influence the results, which limits the usage to

laboratory conditions and to subjects with low body fat percentage [40], [81].

3. **Inclinometer-based**, a sensor constituted by four tri-axial accelerometers [68], aiming the assessment of posture and movement of upper limbs, trunk, and neck, with the line of gravity as reference and two degrees of freedom. The system is able to measure the degree of arm elevation, although it was relative to the vertical line of gravity and not to the trunk. It also could not measure rotation or distinguish arm adduction from arm flexion.
4. **Motion capture** (MoCap) technologies, which includes optical marker-based, optical marker-less, and inertial. These technologies provide a digitalization of the subjects' motion, a promising technique for posture evaluation that has been exploited by many researchers in the last years [69].
5. **Electromyography** (EMG) is the most used method regarding posture strain and muscular fatigue evaluation. It is a technique based on the measurement of the skin's electrical potential through the use of electrodes. There are two types available: intramuscular and surface EMG. Due to the invasiveness of the first, surface EMG sensors are preferred for ergonomic assessment experiments [40].

The Table 3.7 presents a list of direct technologies used to implement direct methods to prevent or reduce the number of MSDs in the workplace and as basis for establishing priorities for intervention. These last two methods, the MoCap technology and the sEMG, have been very popular among the researchers for ergonomic risk assessment, and for the purpose of this study need a deeper analysis.

3.3.1. Motion Capture Technology

In the last years several researchers focused their efforts in the development of novel technologies to ease the measurement of the ergonomic risk of an operator while he is performing manual manufacturing or assembly operations. Motion capture (MoCap) technologies represent a remarkable opportunity to monitor the operator moving in the working environment or in laboratory if evaluations are too complex as presented in Table 3.1. This solution aims at the digitalization of the operator movements and postures along with the geometrical representation of the different body parts in the productive environment [69]. Three different technologies have been developed to ease the tracking of human movements:

- Marker-based optical MOCAP

Table 3.7: Examples of technologies used for biomechanical risk assessment at work [3].

Reference	Technique	Main features	Function
[66]	LMM	Triaxial electronic goniometer.	Assessment of back posture and motion.
[82], [83]	Electronic goniometry	Single or dual plane electronic goniometers and torsiometers to record joint posture.	Measurement of angular displacement of upper extremity postures.
[67], [68]	Inclinometers	Tri-axial accelerometers that record movement in two degrees of freedom with reference to the line of gravity.	Measurement of postures and movement of the head, back and upper limbs.
[40]	Motion capture technology	Optical registration of markers on body segments.	Measurements of displacements, velocities and accelerations of a body segment.
[65]	EMG	Recording of myoelectrical activity from exercising muscles.	Estimation of variation in muscle tension and force application.

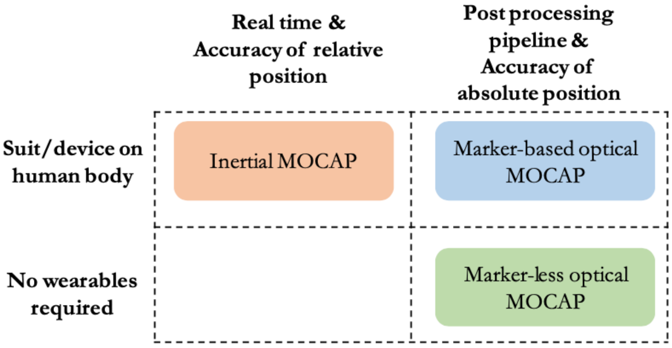
- Marker-less optical MOCAP
- Inertial MOCAP

Marker-based optical MoCap exploits *active* or *passive* markers properly displaced in specific parts of human body. A bunch of cameras detects the position of each marker in its own two-dimensional (2D) field of view, whereas the relative position and orientation of cameras enable to triangulate the location of markers in the 3D space of action. The markers can be either active or passive. Active markers are LEDs which emits light at high frequency. On the contrary, passive markers are small plastic spheres coated with a retroreflective material to reflect the light that is generated near to the cameras lens by an infrared emitter [84]. The absence power supply for markers is the greatest advantage of this latter MoCap configuration. However, optical MOCAP does not offer a real-time representation of the skeleton movements since it requires a time- and resource-consuming pipeline to postprocess the captured data.

Inertial MoCap technology is based on miniaturized inertial sensors which are properly displaced on the body parts. Each inertial measurement unit (IMU) is equipped with a gyroscope, a magnetometer and an accelerometer to record their relative measures on each of the three geometrical axis [85]. The biomechanical model implemented on a proper software offers in a real time fashion the position and rotation of each monitored body part. However, compared to optical MOCAP, the inertial approach is affected by a lower accuracy of the absolute location of the limbs due to positional drift which can compound over the recording time.

Marker-less optical MoCap represents a recent advance in the technology to avoid the suits worn by the human operator in case of marker-based optical or inertial MoCap. Indeed, both these technologies typically mount the active and passive markers as well the IMUs on cumbersome suits. On the contrary, marker-less optical MoCap frees the human actor to perform his activities in his regular outfit. This MoCap system is based on two different camera technologies. Structured light cameras project a band of light on a 3D shaped surface to produce a line of illumination used for the exact geometric reconstruction of the surface shape since the reflected light is not distorted uniquely from the projector perspective. On the contrary, time-of-flight camera emits infrared signals on 3D surfaces and measure the reflected signal through a depth sensor. The comparison between the speed of light and the time of flight to receive back the signals enables to determine the 3D position of each pixel recorded by the camera for each monitored frame [86]. The Table 3.8 classifies the analysed MoCap technologies based on their most relevant features, namely data processing, wearable devices and measurement accuracy.

Table 3.8: MoCap technology classification based on data processing, wearable devices and measurement accuracy.



	Real time & Accuracy of relative position	**Post processing pipeline & Accuracy of absolute position**
Suit/device on human body	Inertial MOCAP	Marker-based optical MOCAP
No wearables required		Marker-less optical MOCAP

3.3.2. Surface Electromyography

Regarding posture strain and muscular fatigue evaluation, the most used method is electromyography (EMG), a technique based on the measurement of the skin's electrical potential through the use of electrodes. There are two types available: intramuscular and surface EMG. Due to the fact that the first one is invasive, surface EMG sensors are preferred for ergonomic assessment experiments [40]. Small-sized and wireless surface electromyography sensors have been exploited for ergonomic assessment. These sensors are non-invasive and provide a direct and objective measurement of physical load exerted on muscles without intruding in the worker's normal activities. Consequently, it has been exploited for assessment of the muscular efforts required by the performed task. sEMG allows the calculation of a lot of parameters regarding muscle behavior such as, among other features, the “activation timing”, the amplitude (maximum values, average rectified values or ARVs, root mean square or RMS) and co-activations. Moreover, a combination of sEMG sensors with MoCap technologies have been proposed in different studies, aiming to complement kinematics data with force exertion for evaluation of the ergonomic risks associated with manual handling of loads [87], [88]. For an overview of the EMG signal, its functioning and analysis see Chapter 4.

3.3.3. Wearable Technology in Ergonomics

Wearable devices are pervasive solutions for increasing work efficiency, improving workers’ well-being [8], reduce work-related injuries and creating interactions between users and the environment [9]. The majority of the available devices are sensor systems composed of different types and numbers of sensors located in diverse body parts. These solutions also represent the technology most frequently employed for monitoring and reducing the risk of awkward postures. Wearable technology extends our capabilities as humans, and epitomises the interaction of humans and technology. An industrial wearable system supports real-time, trusting, and dynamic interaction among operators, machines, and production systems, providing a human-centric empowering technology in Industry 4.0 [37], [89]. The adoption of wearable technology appears particularly interesting for ergonomic purposes because of the well-known properties of assisting the users anywhere, sensing, collecting, and uploading data in a 24 × 7 manner, and monitoring continuously human performance [90]. Ergonomics is the scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and it applies theory, principles, data, and methods to optimise human well-being and overall system performance [91]. In particular, this discipline promotes a holistic, human-centred approach to task, product, environment, and system design and evaluation, considering physical, cognitive, organisational, environmental, and other relevant factors. The traditional domains of specialisation of Ergonomics are the following [91]:

- Physical ergonomics, which is mainly related to human anatomical, anthropometric, physiological, and biomechanical characteristics as they relate to physical activity.
- Cognitive ergonomics, which focuses on mental processes (e.g., perception, memory, information processing, reasoning, and motor response), as they affect interactions among humans and other elements of a system.
- Organisational ergonomics, which is concerned with the optimisation of socio-technical

systems, including their organisational structures, policies, and processes.

3.3.4. Examples of Wearable Devices for Biomechanical risk Assessment at Work

In this section will be presented some examples of wearable devices designed to decrease WR-MSDs, reduce accidents and sick leaves using sEMG an MoCap technologies. These devices, without interfering with the typical movements performed by workers at the workplace thanks to the miniaturization process and wireless protocols, would allow the estimation of biomechanical risk in real-time providing a direct feedback to the end-user who would be constantly monitored directly at work. In this way, the workers could modify their movements during the execution of work tasks thereby reducing and preventing their exposure to the risk of WMSDs.

Myontec

Efforts of research to develop smart wearable systems (SWS) in Ergonomics have been increasing in both academia and industry. Myontec [92] is a company that creates wearable technology that consists of smart clothing with embedded muscle activation level (EMG), upper arm elevation and trunk bending, together with wrist watch measuring heart rate. This smartwear based solution takes biosignal measurements to workplaces and therefore execute the measurements wirelessly. The technology is based on a cell, which has a rechargeable battery and connects to the computer or phone device via Bluetooth. This cell is attached to a piece of clothing (Figure 3.4) which has EMG sensor in contact with the skin. It acts as a first layer, so that the cells get the muscle impulses. The Shirt is the piece of equipment that evaluates upper body muscular activity, in particular the forearm, biceps, triceps, deltoids and trapezius muscles (Figure 3.5).

This technology has been already tested in previous projects and researchers have found it capable of providing comparable muscle excitation data during dynamic tasks. Meaning that this type of technology is a valuable alternative to a more traditional method, making it easier to validate in different environments [93].

AnDy Project

In the near future, robots collaborating with human operators in industries will need more and more anticipation capabilities to properly react to human actions and provide efficient collaboration. These hardware and software technologies are the goal of the European

Figure 3.4: Myontec Shirt [92].

Figure 3.5: Sensors inside the Myontec Shirt. One of the arms (left) and the whole shirt (right) [92].

project AnDy [94]. The AnDy project leverages existing technologies to endow robots with the ability to control physical collaboration through intentional interaction in order to maximize ergonomics for the user. To achieve this goal, AnDy relies on three technologies. First, AnDy develops a wearable AnDySuit (Figure 3.6), which tracks motions and records forces. Second, AnDy develops the AnDyModel, which combines ergonomic models with cognitive predictive models of human dynamic behavior in collaborative tasks, learned from data acquired with the AnDySuit. Third, AnDy proposes AnDyControl, a technology for assisting humans through predictive physical control based on AnDyModel.

By measuring and modeling human whole-body dynamics, AnDy will provide robots with a new level of awareness about human intentions and ergonomics. Technical advances on the AndySuit, using inertial motion capture and sensorized shoes, along with the development of an on-line inverse dynamics software tool now allows real-time monitoring of human dynamics. The information provided thereby is used in the controller of a robot physically interacting with the human, so that the robot reactively adapts its movement to the human's movement. Experiments with a real robot have shown promising results. The next step is to couple the robot controller with an automatic ergonomic assessment tool. Thereby, the robot will be able to detect and anticipate critical situations, and will

Figure 3.6: AnDy set of wearable sensors systems [94].

react in order to optimize the ergonomics of the human movement [94].

Industrial Exoskeletons

Repetitive overhead work has been clearly identified and documented as a type of work that presents a high risk of WR-MSD **cieza2020**, [2]. Several studies [95]–[97] have investigated exoskeletons for overhead work and their effect on the physical stress to the shoulder joint and muscles. These exoskeletons, which are also known as industrial exoskeletons, are external structures worn on the body that provide support for a range of tasks and may improve the user's performance. They have to fulfill high demands on functionality, safety, comfort, and user acceptance in daily work and should therefore be individually adaptable to the anthropometry of the user. These industrial exoskeletons are passive devices that utilize mechanical and/or pneumatic/hydraulic parts to support their users by transferring forces from the upper limbs to the pelvis and/or by storing and releasing energy during movements [96].

The PAEXO passive exoskeleton (Ottobock SE & Co. KGaA, Duderstadt, Germany) has been designed to support overhead work activities [18]. The exoskeleton transfers a portion of the user's arm weight to a hip belt while maintaining the user's freedom of movement. The weight transfer is designed to compensate for the gravitational shoulder torque. The maximum level of support is thus provided at an elevation angle of around 90° (upper arm in horizontal position) and decreases to zero when the arm is lowered to the side of the body. The PAEXO consists of a support structure with an expander that generates the supportive torque via an adjustable lever arm. When the arm is lowered the expander is under maximum tension. In this position, the effective lever arm is zero, meaning that no supportive torque is generated. The PAEXO is connected to the upper arm by an arm brace and a hip belt (Figure 3.7).

Figure 3.7: The passive exoskeleton PAEXO used in industrial environment [98].

A stabilizing structure keeps the exoskeleton close to the body while allowing it to move in a manner comparable to that of the scapula [98]. The movement of the trunk and upper extremities is largely unrestricted. The hip belt, arm brace, and support bar are adjustable for an optimal fit to the user. Despite positive reports describing the benefits exoskeletons offer during overhead work, evidence regarding their functionality as well as possible adverse effects have become the subject to scientific discussion [99]. For example, it is important that the load transfer and possible kinematic changes do not significantly increase strain to other parts of the body, e.g., the lower back or pelvis.

4 | EMG Signal

4.1. Principles of EMG Signal

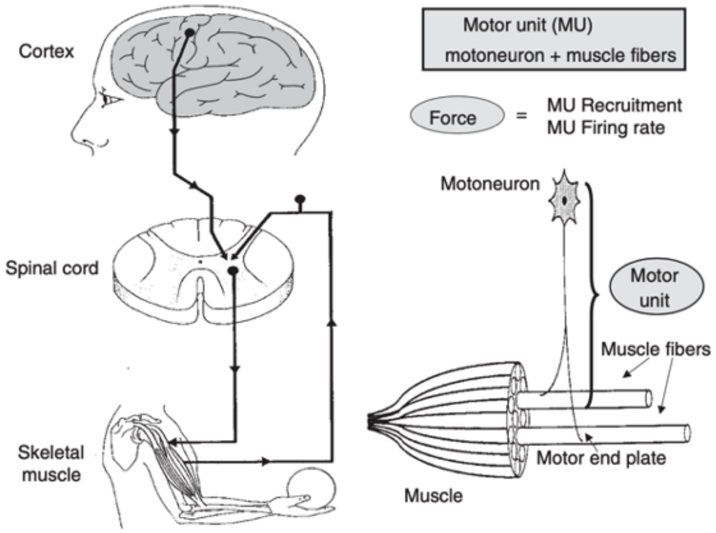
Electromyography (EMG) refers to the collective electric signal from muscles, which is controlled by the nervous system and produced during muscle contraction. The signal represents the anatomical and physiological properties of muscles; an EMG signal is the electrical activity of a muscle's mmotor units and can be of two types: surface EMG, and intramuscular EMG [100]. There are many applications for the use of EMG. It is used diagnostically by gait laboratories and by clinicians trained in the use of biofeedback or ergonomic assessment. EMG is also used in many types of research laboratories, including those involved in biomechanics, motor control, neuromuscular physiology, movement disorders, postural control, and physical therapy. In this Section a detailed analysis of the EMG signal will be presented. First of all we will discuss about the mechanics of the human muscles and of the electromyographic signal in biology, then, in the following paragraphs, commonly used methods for electromyographic signal analysis will be presented.

4.1.1. Generation of the EMG signal

The EMG signal is a biomedical signal that measures electrical currents generated in muscles during its contraction representing neuromuscular activities. The muscle is a contractile organ, which function is to generate force. This force results in motion thanks to the leverage exerted on the bones by tendons attached to muscles. To describe how the EMG signal is generated, we initially consider the smallest functional unit of the neuromuscular system: the motor unit (Figure 4.1) [101]. It is composed of the cell body of the α motoneuron, located in the spinal cord, its axon, the muscle fibers innervated by the same axon and the neuromuscular junction (or motor plate), which allows the muscle contraction following the nerve impulse.

Earlier studies [102] identified three types of motor units based on physiological properties such as speed of contraction and fatigability (sensitivity to fatigue): fast-twitch, fatigable

Figure 4.1: A schematic representation of basic motor control mechanisms and of the motor unit and its components [101].



(FF or type IIb); fast-twitch, fatigue-resistant (FR or type IIa); and slow-twitch (S or type I), which is most resistant to fatigue. In voluntary contractions, force is modulated by a combination of MU recruitment and changes in MU activation frequency (rate coding). The greater the number of MUs recruited and their discharge frequency, the greater the force will be. Voluntary muscular contractions can be classified according to either length changes or force levels. Although the muscle shortens only in concentric contractions, all are typically referred to as "contractions". It is possible to identify five types of contractions:

- *Concentric Contraction*: the force generated is sufficient to overcome the resistance, and the muscle shortens as it contracts. The tension in the muscle decreases as it shortens under load. This factor has been attributed to two main causes. The major reason resides in the fact that there is a loss in tension as the cross-bridges in the contractile element break and then reform in a shortened condition. A second cause appears to be the fluid viscosity in both contractile element and the connective tissue: such viscosity results in friction that requires an internal force to overcome and therefore, results in a reduced tendon force;
- *Eccentric Contraction*: the force generated is insufficient to overcome the external load on the muscle and the muscle fibers lengthen as they contract (an example could be the action of gently lowering an heavy object). There is a relatively limited knowledge about the details of the force-velocity curves of this type of contractions because they are difficult to replicate in a safe manner;

- *Isometric Contraction*: the muscle remains the same length and, even if in tension, it does not produce mechanical work. The contraction can be maximal, if the load is immovable or stationary, if the muscle is used in order to keep the same position;
- *Isotonic Contraction*: the tension in the muscle remains constant despite a change in muscle length. This can occur only when a muscle's maximal force of contraction exceeds the total load on the muscle;
- *Isovelocity* (or Isokinetic) contraction: the muscle contraction velocity remains constant, while force is allowed to vary. Usually this type of contractions are achieved using special devices designed for fitness exercises.

It is possible to assess that muscle tissue conducts electrical potential in a way similar to how axons transmit action potentials. This electrical signal is called Motor Unit Action Potential (MUAP). Electrodes placed on the surface of a muscle (or inside the muscle tissues) are able to record the sum of all MUAPs being transmitted along the muscle fibers at that moment. This signal is called electromyogram. An ionic equilibrium between the inner and outer spaces of a muscle cell forms a resting potential at the muscle fiber membrane (approximately about -80 to -90 mV when not contracted). This difference in potential, which is maintained by physiological processes (ion pump), causes a negative charge inside the fiber compared to the outside. The activation of a motor neuron α (induced by the central nervous system or by a reflex) generates the conduction of the action potential along the axon of the same motor neuron at a speed of about 100 m/s, allowing the release of a neurotransmitter, the 'acetylcholine, at the level of the motor endplates. The presence of acetylcholine at the level of the driving plate causes the opening of the transmembrane channels, through which the Na + ions begin to flow inside the fiber and, more slowly, the K + ions towards the outside of the fiber. This causes a depolarization of the membrane at the level of the driving plate, which is immediately restored by an exchange of ions in the opposite direction, within the active ion pump mechanism and thus repolarization is performed [103] as it is visible in Figure 4.2.

If the membrane potential exceeds a certain threshold value, the depolarization generates a muscle action potential, which rapidly changes the potential from -80 mV up to +30 mV (Fig. 3). This is followed by a rapid restoration of the membrane potential through a repolarization phase, followed by a period of hyperpolarization.

Starting from the motor end plate, the muscle action potential propagates along the muscle fiber in both directions. This excitation leads to the release of Ca ++ ions into the intracellular space. Linked chemical processes (Electro-mechanical coupling) finally produce a shortening of the contractile elements of the muscle cell. Typically, electrodes in

Figure 4.2: Schematic illustration of depolarization / repolarization cycle within excitable membranes [103]

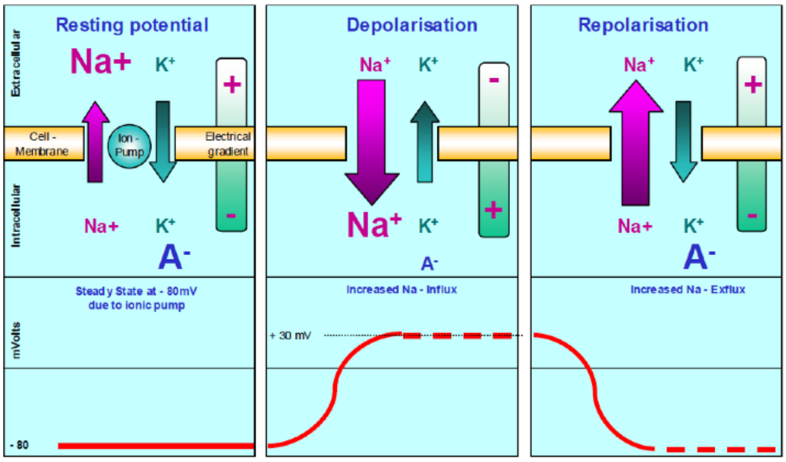


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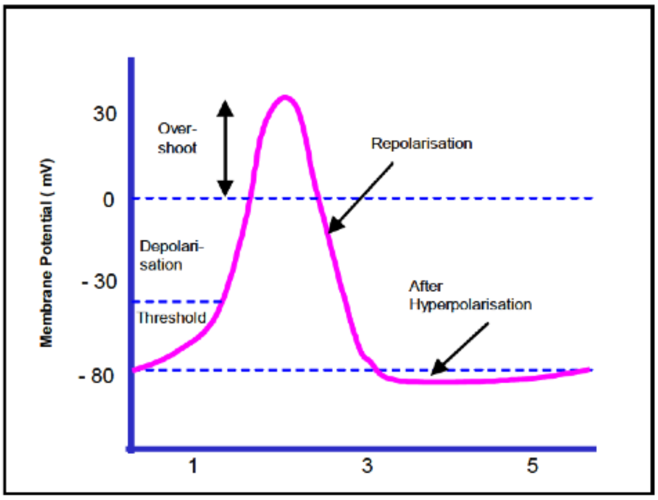
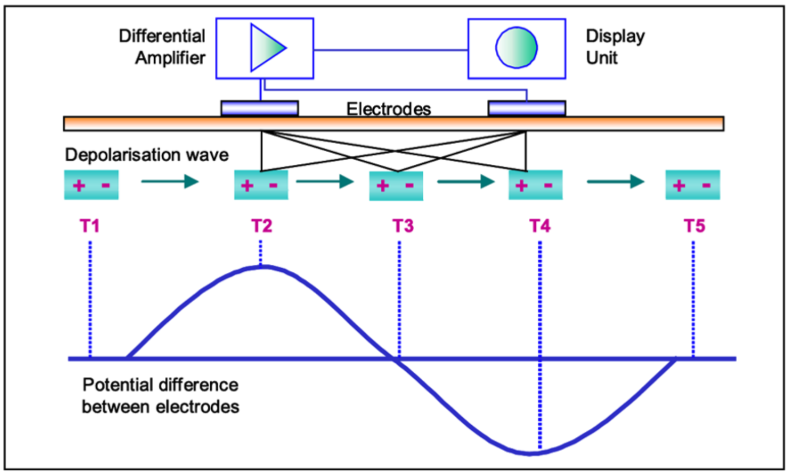
Figure 4.3: The Action Potential [103].



bipolar configuration followed by a differential amplifier are used during the recording of the EMG signal. Since the propagation of muscle action potentials occurs in the direction of the fibers, it will be along this direction that the electrodes for detection will have to be positioned [104].

Referring to Figure 4.4, it is possible to understand how the EMG signal is acquired. There is a pair of electrodes (electrode + on the left and electrode - on the right), positioned parallel to the muscle fibers, which detects the voltage resulting from the currents generated by the potentials action that spread towards it. The action potential is generated at time point T1 and starts traveling towards the electrode pair. An increasing potential difference is measured between the electrodes which is highest at position T2. If the dipole reaches an equal distance between the electrodes the potential difference passes the zero line and becomes highest at position T4, which means the shortest distance to electrode 2.

Figure 4.4: The model of a wandering electrical dipole on muscle fiber membranes [103].

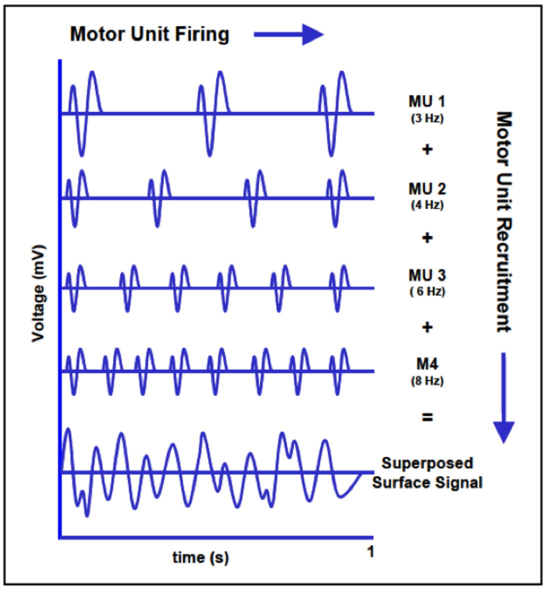


Because a motor unit consists of many muscle fibers, the electrode pair “sees” the magnitude of all innervated fibers within this motor unit, depending on their spatial distance and resolution. Typically, they sum up to a triphasic Motor unit action potential ($MUAP$), which differs in form and size depending on the geometrical fiber orientation in ratio to the electrode site. Within kinesiological studies the MUAPs of all active motor units detectable under the electrode site are electrically superposed and observed as a bipolar signal with symmetric distribution of positive and negative amplitudes (mean value equals to zero). It is called an Interference pattern. The two most important mechanisms influencing the magnitude and density of the observed signal are the Recruitment of MUAPs and their Firing Frequency. These are the main control strategies to adjust the contraction process and modulate the force output of the involved muscle. Because the human connective tissue and skin layers have a low pass filter effect on the original signal, the analyzed firing frequency e.g. of a surface EMG does not present the original firing and amplitude characteristics [103]. For simplicity, one can say that the EMG signal directly reflects the recruitment and firing characteristics of the detected motor units within the measured muscle (Figure 4.5).

4.1.2. Recording of EMG signal

The electromyographic signal can be detected with different types of electrodes and amplified in various ways. The electrodes are real transducers that transform the ionic currents generated in the muscles into an electronic current that can be manipulated with

Figure 4.5: Recruitment and firing frequency of motor units modulates force output and is reflected in the superposed EMG signal [103].



electronic circuits and stored in analog or digital form as a voltage potential.

The classification of the electrodes is based on several criteria, such as: the detection site (depth and surface electrodes) and the type of configuration (monopolar and bipolar electrodes).

Depth and Surface Electrodes The two methods are better suited for a different span of applications and have their own advantages and disadvantages and are therefore both currently used for EMG signal detection. The choice of electrode depends on the motor task to be explored, the nature of the research question and the specific muscle that has to be analyzed.

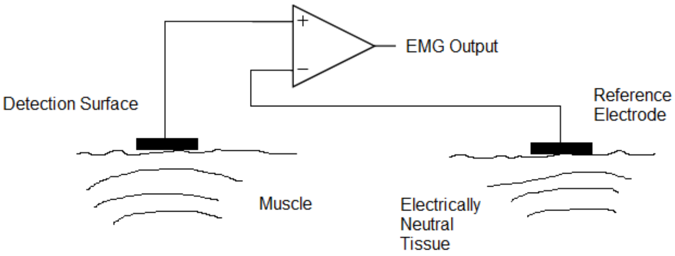
- **Depth electrodes** are inserted inside the muscle tissue, thus allowing the study of deep muscles. They are able to detect the signal of a small number of motor units, thanks to the reduced picking surface which makes them more selective. This therefore allows us to investigate different areas within the same muscle. The main disadvantage is their invasiveness and poor tolerability by the patient. Due to muscle movements within kinesiological studies, thin and flexible fine wire electrodes are the preferred choice for invasive electrode application within deeper muscle layers.
- **Surface electrodes** are metal discs, with a diameter of less than 1 cm, which are applied to the skin in correspondence with the muscle to be examined. Their main limitation is that they can only be used to analyze superficial muscles. As the

electrode diameter and the interelectrode distance decrease, the working volume decreases and therefore the selectivity of the measurement increases and cross-talking decreases. The most used are the Ag / AgCl electrodes equipped with gel, easy to apply and disposable. Commercial disposable electrodes are made with wet gel or adhesive gel. Generally, the wet gel electrode allows better conduction and lower impedance values between the electrode and the skin than the adhesive gel electrode. The latter, however, has the advantage that it can be repositioned in the event of errors.

Monopolar and bipolar electrodes

- **Monopolar configuration**: the muscle potential is detected by one electrode, which has another electrode as a reference. The problem in this case is the low spatial resolution, in fact every electric potential between the detecting and the reference electrodes are sampled and amplified. This means that unwanted signals, like the ones coming from other muscles or the ones from the capacitive coupling with the line voltage, are also gathered (see Figure 4.6).

Figure 4.6: Monopolar configuration. Source: NR Sign Inc.

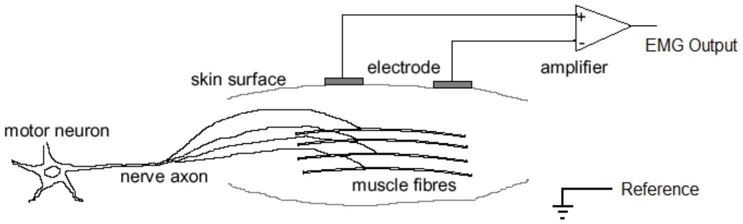


- **Bipolar configuration**: the spatial resolution is increased and the noise reduction is improved. This configuration is normally connected to an operational amplifier, having as inputs the two signals. Therefore the difference between two monopolar signals is amplified, and the information common to both electrodes is removed. Thereby, a large part of the unwanted noise and of the cross-talk, which are normally common to both electrodes, is eliminated (see Figure 4.7).

4.2. Surface Electromyography (sEMG)

Detected by surface electrodes, the electromyographic signal has to be considered as a stochastic process. Raw sEMG can range between +/- 5000 µV and typically the fre-

Figure 4.7: Bipolar configuration. Source: NR Sign Inc.



quency contents ranges between 6 and 500 Hz, showing most frequency power between 20 and 150 Hz. In order to record the EMG signal, a biological signal acquisition system is needed. An ideal acquisition consists in registering a summation of MUAPs undistorted and free of noise, but it is an almost impossible task [105].

While passing through varied tissues and electronic equipments EMG signal is contaminated by various noises. It's important to know the properties of those unwanted electrical signals. We can classify the electrical noises affecting the EMG signal into the following [106]:

Motion artifact. This type of noise consists of frequency range between1-10 Hz. The voltage extend is similar to the amplitude of the EMG signal. The informative signal gets distorted with the interference of such artifacts. This makes abnormalities in the signal. This is basically because of the adjustments in the muscle and its relative movement. There are chances of movement of electrodes with respect to each other on skin. Additionally, when the muscle is enacted, it decreases the length of muscle. Consequently, electrodes will generate motion artifacts. Interfacing of electrodes with skin and electrode cables are the primary source of motion artifacts. Appropriate plan of the electronic hardware is the best way to lessen this noise.

Inherent noise in electronics equipment. This type of noise is inherent in every electronic equipments. This noise can't be eliminated. This will solely be reduced by accurate elements and use intelligent circuit style. By using silver or silver chloride electrodes the adequate level of signal to noise ratio can be acquired. Impedance of the system is inversely proportional to the size of electrode.

Ambient noise. The amplitude of the electromagnetic noise is about 100-300 V. On the surface of earth human body surface consistently expose to the electromagnetic radiations and is impossible to avoid such exposure. Power line interface (PLI) is that the close noise inflicting from the radiation of power sources of 60Hz or 50Hz. If the frequency of this interference is high, then it is removed by employing a high pass filter or a notch filter.

it's necessary to understand the character of the EMG signal, if the frequency content of PLI is among the EMG signal.

ECG artifacts. The way toward recording the electrical action of heart is alluded to as the electrocardiography. The ECG is a meddling segment in the EMG signal taken from the shoulder girdle, which is termed as ECG artifact. The EMG taken from the muscles in the storage compartment are frequently gets influenced by ECG artifacts. The EMG electrode position is a significant factor that decides the reach out of ECG tainting in EMG signal. As the frequency spectra of ECG and EMG signals gets overlap and furthermore as the attributes, for example, nonstationary and shifted fleeting shape are comparative with one another, the expulsion of ECG artifacts from EMG signals are so troublesome.

Cross-talk. It refers to a signal contribution originating from other muscles. In biomedical field this problem is avoided employing needle electrodes that are directly inserted into the muscle that must be analyzed. Obviously needle electrodes are not suitable for any application, and thus signal processing stage needs to provide the appropriate signal filtering to remove crosstalking. Despite the fact that this can be because of different parameters, via cautiously picking the electrode size and between terminal separations, this can be limited.

Transducer noise. This noise is delivered at the electrode skin junction. Electrodes act as transducers and converts ionic current into electrical current produced by the muscles contraction which can easily recorded as analog or digital voltage potential signal. AC voltage potential and DC voltage potential are two major sources of such noise. The impedance impact is the primary cause for this noise, and this can be diminished by utilizing Ag-AgCl electrodes.

4.3. Signal Processing and Analysis

EMG signals acquired from muscles require advanced methods for detection, decomposition, processing, and classification. The purpose of this Section is to illustrate the most common methodologies and algorithms for EMG signal analysis to provide efficient and effective ways of understanding the signal and its nature.

Full Wave Rectification

In a first step all negative amplitudes are converted to positive amplitudes, the negative spikes are "moved up" to plus or reflected by the baseline. Besides easier reading the main effect is that standard amplitude parameters like mean, peak/max value and area can be applied to the curve (raw EMG has a mean value of zero) [103].

Smoothing

The interference pattern of EMG is of random nature; a raw EMG burst cannot be repro- duced a second time by its precise shape [101]. To address this problem, the non-reproducible part of the signal is minimized by applying digital smoothing algorithms that outline the mean trend of signal development. The steep amplitude spikes are cut away; the signal receives a "linear envelope". Basically two algorithms are established:

- **Moving average (Movag)** Based on a defined time window, a certain amount of data are averaged using the sliding window technique. If used for rectified signals it is also called the Average Rectified Value (AVR) and serves as an "estimator of the amplitude behavior" (SENIAM). It relates to information about the area under the selected signal epoch.
- **Root Mean Square (RMS)** Based on the square root calculation, the RMS reflects the mean power of the signal (also called RMS EMG).

Amplitude Normalization

To be able to compare EMG activity in the same muscle on different days or in different individuals or to compare EMG activity between muscles, the EMG must be normalized. Normalization of EMG signals is usually performed by dividing the EMG signals during a task by a reference EMG value obtained from the same muscle. By choosing a reference value repeatable within an individual, one can compare the levels obtained from any task to that reference value. The choice of reference value should allow comparisons between individuals and between muscles. The most common method of normalizing EMG signals from a given muscle uses the EMG recorded from the same muscle during a maximal voluntary isometric contraction (MVC) as the reference value. The process of normalization using MVCs is that a reference test (usually a manual muscle test) is identified which produces a maximum contraction in the muscle of interest. The EMG signals are then processed either by high-pass filtering, rectifying and smoothing or by calculating the root mean square of the signal. The maximum value obtained from the processed signals during all repetitions of the test is then used as the reference value for normalizing the EMG signals, processed in the same way, from the muscle of interest. Other normalization methods exploit the peak or mean activation levels obtained during the task under investigation. The main effect of all normalization methods is that the data are scaled to percent of selected reference value.

Amplitude-related parameters

EMG traces can be calculated with standard amplitude parameters, such as mean, peak, minimum value, area and slope. The preliminary condition is rectification, due to the bipolar signal nature.

- The **EMG Peak value** is only meaningful for averaged curves because even for smoothed rectified EMG traces, it is still too variable.
- The **amplitude Mean** value of a selected analysis interval is one of the most important EMG-calculation, because it is less sensitive to duration differences of analysis intervals. The mean EMG value best describes the gross innervation input of a selected muscle for a given task and works best for comparison analysis.
- **Area** is the true mathematical integral under the EMG amplitude for a certain analysis period. Depending on the point of view, it has the benefit or drawback of being directly dependent on the time duration selected for an analysis.
- **iEMG** means integrated EMG and is defined as the area under the curve of the rectified EMG signal; that is, the mathematical integral of the absolute value of the raw EMG signal.

Frequency-related parameters

While time domain can demonstrate a tendency of signal change over time, however on the other hand, the frequency domain comes with the ability of demonstrating the distribution of all involving power frequency spectral, which consist of the fundamental frequency and other remaining different harmonics. All of those power frequency spectrum generally has a boundary across the band pass filter length, that normally is set between 10 – 500 Hz, which is considered as much suitable for surface EMG (SENIAM).

There are two fondumental frequency spectral parameters: mean frequency (MNF) and median frequency (MDF) [107]. Both parameters are responsible to represent the central tendency of the power frequency spectrum, but with a different definition as could be described as following:

- The **mean frequency** (MNF) is an average frequency which is calculated as the sum of products of the EMG power spectrum and the frequency divided by the total sum of the power spectrum.

- The **median frequency** (MDF) MDF is a frequency at which the EMG power spectrum is devided into two regions with equal amplitude. MDF is also defined as a half of the total power. [101].

5 | Objectives, Design and Development

5.1. Framework and Objectives

According to international statistics, in the last years Musculoskeletal Disorders (MSDs) have become one of the main concern for workers health and safety [16]. When MSDs are caused or aggravated primarily by work itself, these can be defined as work-related MSDs. As widely discussed in Chapter 2 Work-related MSDs arise from regular exposure to a certain load and it is a problem that affects all forms of working environments, from physically arduous work to low-intensity static work. In order to reduce the risk of WR-MSD several methods have been developed, accepted by the international literature and used in the workplace as presented in Section 3.1. These approaches have without doubt facilitated prevention activities during the last decades by improving occupational health and safety of people at work but, on the other hand, need a significant update based on some aspects. First, the standardized methods commonly used for biomechanical risk assessment are still mainly based on observational and subjective approaches [45], [60], [108] and don't include instrumentation-based tools. Second, the recent widespread use of robots, automation and mechanization in industry for the reduction of the physical effort has modified manual handling work activities. One of the key technologies driving this epochal change, the human-robot collaboration (coRob) technology [109], is invading several areas of the industry. The nascent nature of CoRob in the workplace conceives the safe coexistence and interaction of workers and robots within the same environment allowing a significant transformation of the current static automation environs into adaptive, flexible and reconfigurable ones. In particular, the presence of the most advanced remotely controlled robot, occupational collaborative robots will assist more and more workers in performing their tasks reducing their exposure to the associated physical risks [108], [109]. In view of this new workplace setup it is questionable whether the standardized biomechanical risk assessment methods are able to take into account all these new factors or not.

Wearable devices constitute an emerging approach [9], and are excellent candidates for supporting human activities and improving quality of life. They represent a new means of addressing the needs of many industries, and have the potential to increase work efficiency among employees, improve workers' physical well-being, and reduce work-related injuries [8], [110]. While advances in wearable wireless sensor networking have lead the way for new possibilities in clinical applications [111], [112] and sport performance measures [113], today their potential for biomechanical risk assessment is still largely underexploited [108]. The most innovative wearable technologies and electronic smart devices may improve the biomechanical risk assessment by adapting it to all the work conditions and overcoming the limits of the current standardized methods. For instance, intelligent work environments [114] may represent the new scenario in which smart wearable sensors with computational capabilities and network connection are sensitive, responsive, adaptive and transparent to workers' movements allowing real-time monitoring of work activities [108]. Thus, these devices, without interfering with the typical movements performed by workers at the workplace thanks to the miniaturization process and wireless protocols, would allow the estimation of biomechanical risk in real-time providing a direct feedback to the user who would be constantly monitored directly at work. In this way, the workers could modify their movements during the execution of work tasks thereby reducing and preventing their exposure to the risk of WR-MSDs.

5.2. WINGS - Wearable Industrial Gear

LWT3 is developing a wearable computer system specific for monitoring working activities with a double purpose:

- to reduce the workplace injury and the related financial and social impacts;
- to enhance the interaction with other workers, tools, machines and coBots.

The wearable system is a washable smart garment, more specifically, a sleeveless shirt and shorts with integrated electronic systems with embedded signal processing and transmittance in order to monitor the muscular effort and other features from biological signals during working activities. The structure of the system allows the acquisition, analysis and display of data concerning the user, the machine and preferably also the environment in which they are, so as to further improve the quality of life of the operator and of the production processes. The system components also allow to collect and store automatic learning patterns to guide the improvement of ergonomics, safety and collaboration during various tasks that involve physical stress, such as repetitive and/or heavy assembly line work, handling of goods, hospital care and so on. In particular, the control subsystem allows to warn and advise the specific operator on the best type of movement in order to preserve his health and to send control data to the machines to optimize their behaviour according to the specific operator and his specific state at that time, such as posture, fatigue, muscle stress, heart rate and other parameters acquired by the wearable device or by the external sensors.

The system is composed by the wearable device which is embedded with sEMG sensors and more specifically carbon black based electrodes, and other sensors suitable to measure further parameters of the user. The suit is made of flexible and stretchable materials capable of maintaining conductive properties. Each garment (shorts and shirts) is equipped with one wireless data processing and transmission system in a compact and wearable format (see Figure 5.1).

Figure 5.1: WINGS wearable components. Left: sensorized Shirt and Shorts. Right: wireless data processing and transmittance system embedded into the shirt and shorts.

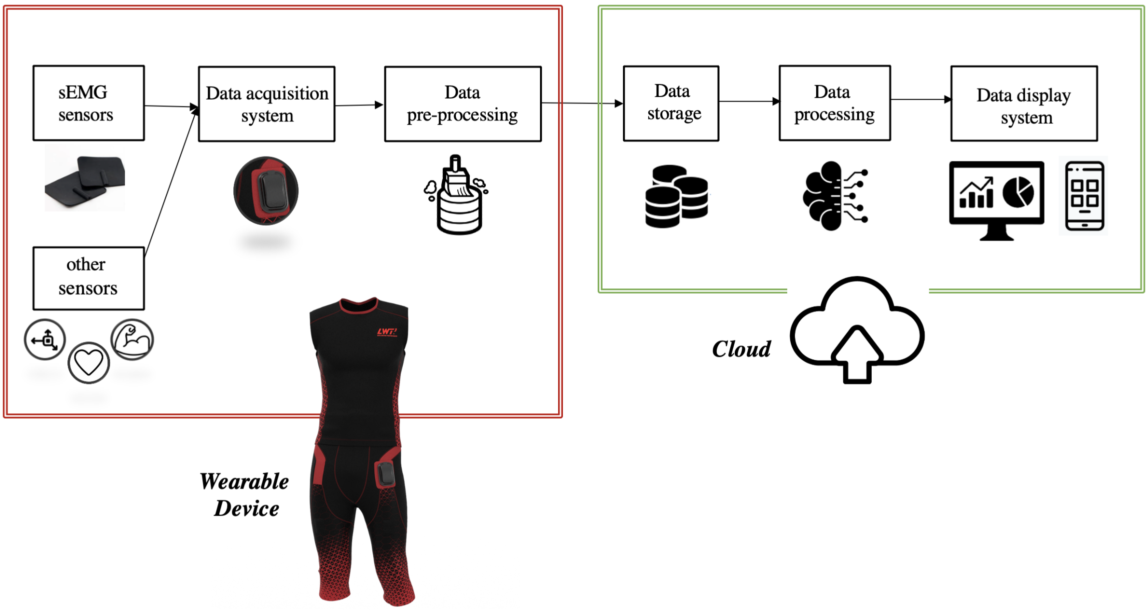
It's important to specify that the muscles electric activity of all the target muscles is recorded and transmitted to a unique wireless system integrated into the shirt (RAW POWER EMG board). The routing of the electrode cables from each electrode pad to the EMG board cannot be mentioned in this thesis as they are reserved information the company explicitly asked to do not distribute externally. The aforementioned design and electronic choices classify the product; therefore thought to be worn outside the laboratory environment by a large number of workers on everyday working activities.

The WINGS components and pipeline comprise (Figure 5.2):

- Recording of the sEMG signals from the target muscles (the selection of muscle groups on which place the electrode pads is presented in Section 7.1.1);

- Data acquisition system embedded into the wearable device and suitable to receive, aggregate and pre-process the data received from the textile electrodes;
- Data storage system suitable to store the data received from the sensors and/or processed by the data processing system;
- Data processing system suitable for further processing and mining;
- Data display system suitable to display the data received from the sensors and/or processed by the data processing system.

Figure 5.2: A schematic representation of WINGS pipeline.



The stakeholders are, first and foremost Insurance Companies who reap the financial and social benefits associated with the increase of quality of life and data analysis related to injuries. Second and obviously, the stakeholder is the worker who profits directly from the wearable device, either because the smart clothes contributes for a betterment of the user's quality of life and a reduction of work related injuries due to personal physical assessments and predictive analytics retrieved from the wearable system. Other stakeholders are Factories which may improve processes and productivity, and finally the Machine and Robot Designer may achieve important data for new types of tools and UX/UI or to improve working conditions by redesigning existing static automation environs into adaptive and flexible ones.

5.3. Contributions of this thesis

The work presented in this thesis and my contribution to LWT3 project was based on a double frontier. First, I worked with the Design Team for the design and development of the Smart Garment prototype. Second, I developed a Protocol that aims at simulating working tasks in a laboratory environment with the purpose to register the activation and deactivation patterns of target muscles correlated with the simulated task.

As concerns the design and development of the Smart Garment I supported the team to determine the muscles to be investigated and the related electrode pads to embed into the Vest. The muscles selected are the result of a long and deep literature research and are established according to specific design constraints (see Section 7.1). Once the muscles groups were defined, in order to design and produce the first prototype the correct placement of the electrodes on the shirt was fundamental. To acquire the best possible signal, the sEMG electrodes should be placed at a proper location and the orientation across the muscle is also important. For the purpose of finding the optimal positioning, a series of Muscle Isolation tests were conducted. These tests aim at isolating the activity of a target muscle with respect to adjacent muscles by performing a specific movement in a determined position.

Regarding the Protocol development, the objective is to define a replicable acquisition method that simulate different working task, such us lifting of loads, handling of low loads at high frequency, pushing and pulling, work in prolonged standing posture, etc., aiming at gathering task based muscular activation and deactivation patterns. The protocol used will be then the same when assessing different working tasks since it represents a methodology: same technologies, target muscles, subject preparation and setup; only the movements that define the job task would differ. In order to validate this protocol a case study was conducted in LWT3 Laboratory and the experimental procedures carried out are described in Section 7.2.2. The case study represent the simulation of the work performed by a cashier or workers engaged in repetitive manual handling of loads that represents one of the main risk factors for WR-MSD (analyzed in Section 2.4). The selected task is classified by the Occupational Safety and Health Directives (OSH) as *Manual Handling of Low Loads at High Frequency* and therefore the parameters that define the working activity (e.g. frequency, duration and workstation setup) are defined with reference to the OSH standards currently in force. The definition of the Protocol used to perform the test is described in Section 7.2.

6 | Materials

For the realization of this study it was necessary to use an experimental set up for the acquisition of the electromyographic signals and the kinematic data in order to identify common patterns during a simulated task of low load manual handling at high frequency.

The main components of the experimental setup are:

- Electromyography board,
- Push-pull circular connectors,
- sEMG electrodes,
- Optitrack MoCap System with 6 cameras,
- Workstation and Software.

6.1. Electromyography System

Surface EMG signals were recorded using an eight-channel proprietary EMG system with the following specifications:

- Configuration: DD (Double Differential)
- Sampling frequency:
    - Minimum 500 Hz
    - Maximum 2.7 kHz
    - In this study 1 kHz
- ADC resolution: 22 bits
- Power supply and data transfer: USB 2.0
- Processor: ARM M4 CPU Architecture
- Electrodes electrically isolated from the power supply

Figure 6.1: EMG board.

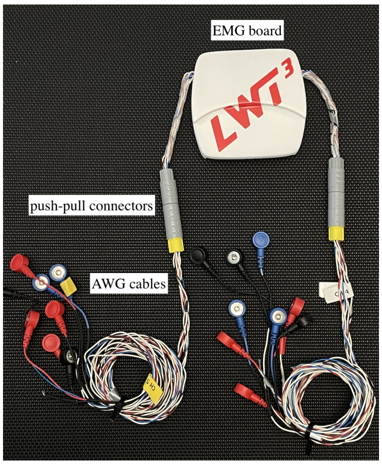
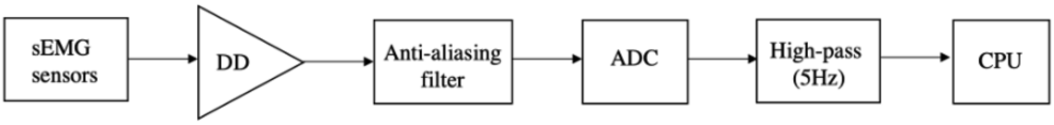
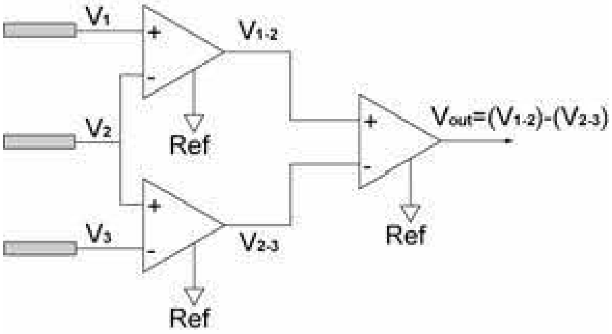


Figure 6.2: Architecture of the Raw Power EMG board with the main components.



The double differential configuration requires three aligned electrodes and computes the difference between two adjacent bipolar signals (Figure 6.3) enhancing the rejection of contributions from far sources (therefore reducing the detection volume and increasing spatial selectivity) and reducing the effects of the innervation and termination zones [101], [107].

Figure 6.3: Double Differential (DD) configuration.



The AWG shielded cables from preamplifiers are paired and wired to two 9-pin push-pull connectors (ODU MEDI-SNAP, Mouser Electronics, Inc., Mansfield, Texas (USA)) visible in Figure 6.1.

6.2. sEMG Electrodes

The electrodes used in the experimental phase are standard EMG electrodes, circular and conductive area of with 1 cm square, in FOAM, clip in Ag/AgCl, pregellated, disposable, produced by TOP TRACE (Figure 6.4).

Figure 6.4: Electrode type used in the experimental study.

The main challenges in wearable sensing is the development of bioelectrodes via the use of flexible and stretchable materials capable of maintaining conductive and biocompatible properties simultaneously, and since the electrodes need to be embedded in the smart garment the prototype and the final smart garment will be embedded with carbon black electrodes.

6.3. Optitrack Motion Capture System

The most widespread technological solution for the analysis of human movement is represented by optoelectronic Motion Capture Systems, which allow for a non-invasive three-dimensional kinematic survey. These are systems based on the use of optical markers, positioned on the subject's body in particular anatomical landmarks, and a variable number of cameras operating in the infrared. Our study was carried out at the LWT3 Laboratory, which is equipped with an OptiTrack Motion Capture system (NaturalPoint, Inc., Corvallis, OR) for motion analysis [115] and operated using OptiTrack Motive 1.10.1 software (NaturalPoint, Corvallis, Oregon, USA).

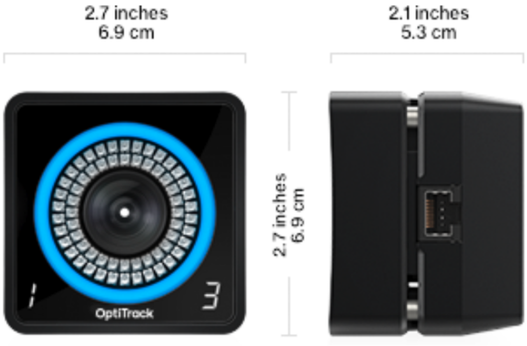
Figure 6.5: Passive markers.

(a) Reflective markers for optical capture of movement, with circular velcro base.

(b) Markers specifications.

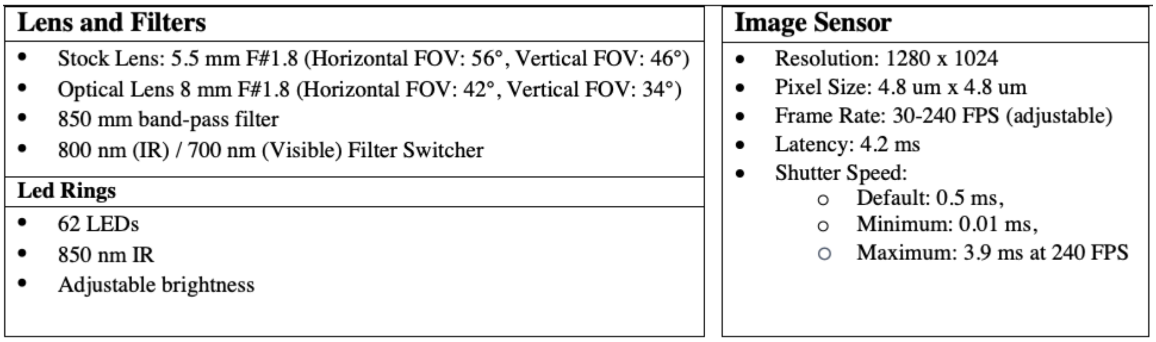
The optical markers used are spherical in shape (14 mm diameter) and made of reflective material (see Figure 6.5) so that the infrared light emitted by the LED rings arranged on circular rings coaxial with the camera is reflected and can therefore be detected by the system of lenses and addressable matrix sensors (Figure 6.7).

Figure 6.7: Optitrack Camera [115].



The system consists of 6 cameras arranged to cover the entire work volume and so that each marker can be detected simultaneously by at least 2 cameras in order to be able to calculate the three-dimensional coordinates of each marker. The captured space used for MoCap acquisitions has an extent of 300 cm x 400 cm x 250 cm, an overhead view of which can be seen in Fig 6.8. The cameras specifications are presented in Table 6.1.

Table 6.1: Optitrack Camera specifications [115].



Lens and Filters

- Stock Lens: 5.5 mm F#1.8 (Horizontal FOV: 56°, Vertical FOV: 46°)
- Optical Lens 8 mm F#1.8 (Horizontal FOV: 42°, Vertical FOV: 34°)
- 850 mm band-pass filter
- 800 nm (IR) / 700 nm (Visible) Filter Switcher

Led Rings

- 62 LEDs
- 850 nm IR
- Adjustable brightness

Image Sensor

- Resolution: 1280 x 1024
- Pixel Size: 4.8 um x 4.8 um
- Frame Rate: 30-240 FPS (adjustable)
- Latency: 4.2 ms
- Shutter Speed:
  - Default: 0.5 ms,
  - Minimum: 0.01 ms,
  - Maximum: 3.9 ms at 240 FPS

To proceed with the 3D reconstruction, it is essential to calibrate the system before each homogeneous series of kinematic acquisitions. This procedure requires defining the calibration volume and the absolute Cartesian reference system (origin and orientation of the axes in the laboratory) and allows to determine the internal parameters (focal length, coordinates of the main point and distortion coefficients) and external (position of the camera reference system compared to the absolute reference system) of the cameras.

The determination of the geometric parameters of the cameras involves the use of a set of control points, distributed internally in the calibration volume. In the calibration procedures, the coordinates of the control points must be known in advance. For this purpose, fixed-shape objects are used in which the control points are placed on a rigid

Figure 6.8: LWT3 Laboratory view and cameras arrangement.

structure and the distance between them is measured with a priori accuracy (see Figure 6.9).

Figure 6.9: Optitrack Calibration tools [115].

(a) Wand. (b) Ground tool

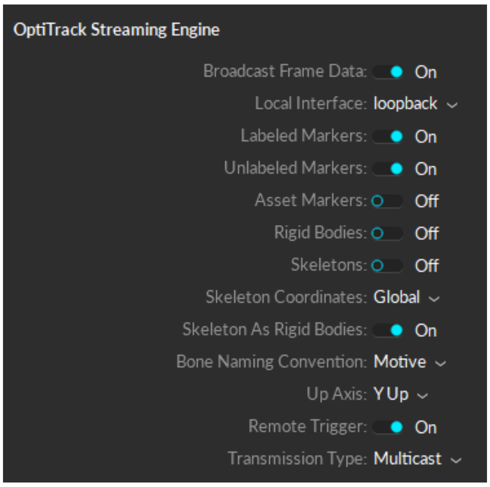
6.4. Workstation and Software

The EMG And MoCap instrumentation is managed from the LWT3 laboratory workstation using the RAW POWER software dedicated to sEMG recording and analysis, with which it was possible to acquire and process the electromyographic signals in synchronization with the kinematics data recorded by the connected optoelectronic system

(OptiTrack Motive software NaturalPoint, Corvallis, Oregon, USA).

Motive is OptiTrack's software platform and has been firstly used for camera calibration using the Calibration Kit component shown in Figure 6.9. After the calibration of the system the frame data is streamed on the same machine but to a different application. Both server (Motive) and destination application (STT Systems Software San Sebastián, Spain [116]) are running on the same machine then the network interface to the local loopback address (see Figure 6.12).

Figure 6.11: Optitrack streaming engine [115].



OptiTrack Streaming Engine

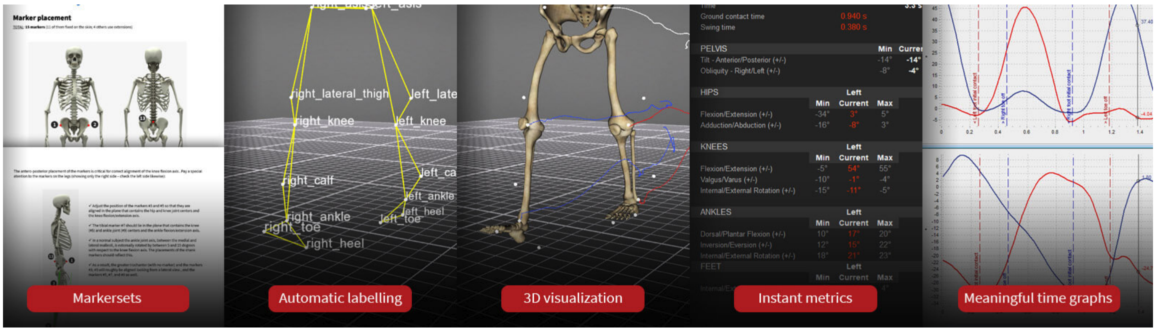
Broadcast Frame Data: On
Local Interface: loopback
Labeled Markers: On
Unlabeled Markers: On
Asset Markers: Off
Rigid Bodies: Off
Skeletons: Off
Skeleton Coordinates: Global
Skeleton As Rigid Bodies: On
Bone Naming Convention: Motive
Up Axis: Y Up
Remote Trigger: On
Transmission Type: Multicast

3DMA STT Software is a family of products for biomechanical analysis based on optical motion capture addressed to clinical, sport and industrial use. The software permits to have data concerning not only positions of markers on XYZ axes but also data related to joint kinematics on sagittal, frontal and transversal plane and events recognition such as gait analysis events and more. This tool is very useful and give a variety of pre-processed information and features.

The software supports several protocols and each protocol is made up of analysis components that help conduct the analysis very efficiently. These components are: the predefined markersets, the auto-labelling algorithm, a 3D scene definition with visual elements, a dashboard with real-time calculations, and graph modules [116].

The use of STT software is essential for next phases development of LWT3 project that will see the results and data acquired during this study applied to future implementations and analysis. In this study the software is used to obtain kinematics data and to verify that the task is correctly executed by the subjects.

Figure 6.12: Example of 3DMA STT Software components [116].



Ground contact time	0.940 s
Swing time	0.380 s

PELVIS	Min	Curren
Tilt - Anterior/Posterior (+/-)	-14°	-14°
Obliquity - Right/Left (+/-)	-8°	-4°

HIPS	Left		
	Min	Current	Max
Flexion/Extension (+/-)	-34°	3°	5°
Adduction/Abduction (+/-)	-16°	-8°	3°

KNEES	Left		
	Min	Current	Max
Flexion/Extension (+/-)	-5°	54°	55°
Valgus/Varus (+/-)	-10°	-1°	-4°
Internal/External Rotation (+/-)	-15°	-11°	-5°

ANKLES	Left		
	Min	Current	Max
Dorsal/Plantar Flexion (+/-)	10°	17°	20°
Inversion/Eversion (+/-)	12°	15°	22°
Internal/External Rotation (+/-)	18°	21°	23°

FEET	Left		
	Min	Current	Max

7 | Methods

The present work has been conducted in collaboration with LWT3 and it is a part of the research and development of a new system for evaluating human ergonomics, reducing risks associated with working tasks and preventing MSDs.

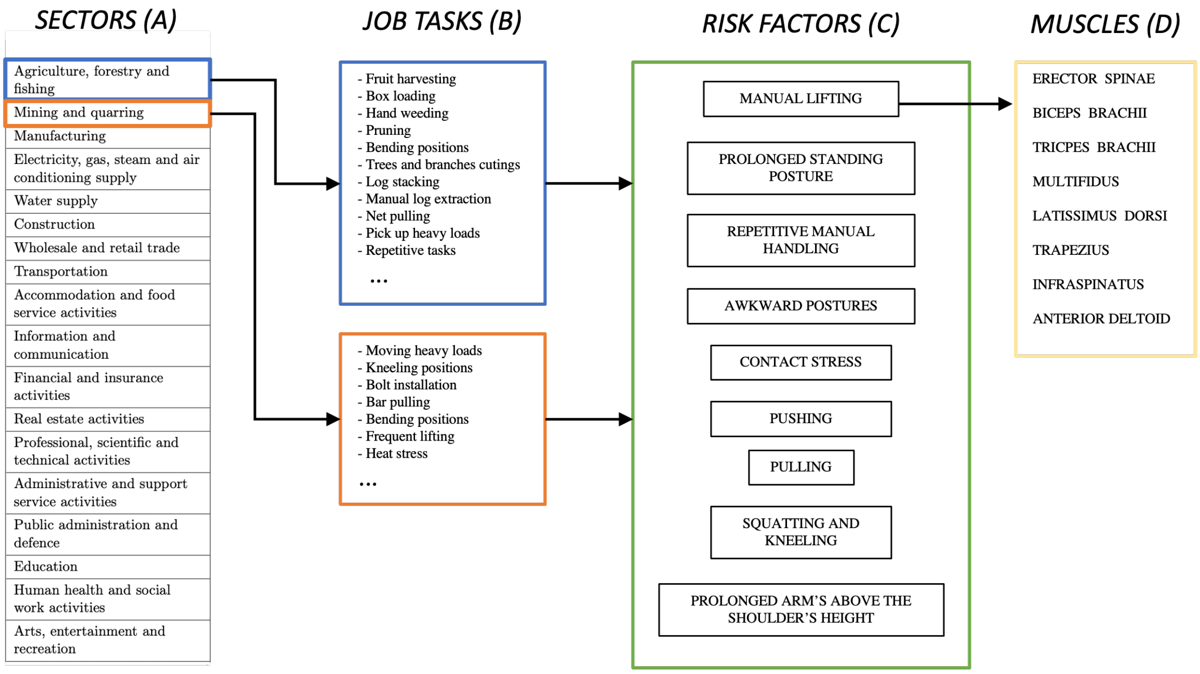
The experimental procedures carried out and presented in this chapter are divided in two parts:

- The first part concerns the support provided to the Design Team in the development of the wearable device and specifically in the selection of muscles groups (Section 7.1.1) to be embedded into the wearable device prototype and the *Muscle Isolation Tests* (Section 7.1.2) carried out to determine the placement of the textile electrodes;
- The second part regards the definition of the *Acquisition Protocol* that aims at presenting a method that permits to simulate working tasks in a laboratory environment with the purpose to register the muscles activity patterns. The Protocol definition is presented in Section 7.2. Then the validation of the protocol and the experimental procedures carried out are described in Section 7.2.2.

7.1. Supporting Smart Garment Design and Development

This section will present the study and the workflow (outlined in Figure 7.1) that led to the selection of the muscles to be embedded into the smart garment prototype, in line with the design constraints, and the consequent tests conducted to find the best positioning of the textile electrodes on the selected muscles. The electrodes placement is fundamental fin order to acquire reliable data and a good quality of the sEMG signal.

Figure 7.1: The figure represents the workflow of the literature and statistical research made in terms of correlation between the most *WR-MDSs* and the main *Job tasks* carried out in those sectors. The job tasks of each sector were then clustered in general work related risk factors such as: lifting of loads, kneeling posture, prolonged standing posture, raised arms working posture, etc. For each type of risk factors, the most involved and overstressed muscles have been identified. The correlated research allowed to obtain the most overload and fatigued muscles during the execution of the working tasks carried out in the sectors with the greatest number of WR-MSDs reported. In this Figure is reported only the research flow made for two sectors: the Agricolure/Forestry/Fishing and the Mining/Quarring while the others are presented in Table 7.2.



7.1.1. Muscles Selection

The starting point regards the statistical research on the prevalence of self-reported MSDs between sectors. The purpose of this research was to report which are the sectors that mainly report injuries and MSDs pathologies. Statistically, the sectors most involved are shown in Table 7.1.

Once the working sectors, that mostly report injuries and musculoskeletal pathologies, were identified a further research was centered on the specific job tasks of each sector. For instance, in the agriculture sector, examples of target tasks identified are: fruit and vegetable harvesting, lifting boxes, pruning, picking grapes which involve postures with raised arms, picking tomatoes and other vegetables which involve postures with bent back, etc. (section B in Figure 7.1).

The output of phase B is a list of work tasks for each sector, which then were clustered

Table 7.1: Percentage of workers reporting MSDs in the backache, upper limb and lower limb in the past 12 months, by sector (NACE rev. 2), EU-28, 2015

Sectors	**Backache**	**Upper Limb**	**Lower Limb**
Agriculture, forestry and fishing	60%	56%	46%
Mining and quarring	40%	51%	30%
Manufacturing	46%	43%	28%
Electricity, gas, steam and air conditioning supply	42%	43%	24%
Water supply	53%	49%	40%
Construction	42%	54%	41%
Wholesale and retail trade	42%	40%	30%
Transportation	46%	37%	26%
Accommodation and food service activities	43%	41%	35%
Information and communication	40%	41%	20%
Financial and insurance activities	32%	30%	17%
Real estate activities	45%	39%	24%
Professional, scientific and technical activities	36%	35%	18%
Administrative and support service activities	43%	42%	32%
Public administration and defence	38%	39%	27%
Education	36%	35%	22%
Human health and social work activities	47%	46%	31%
Arts, entertainment and recreation	44%	31%	27%

Adapted from Panteia based on the sixth (2015) wave of the European Working Conditions Survey (EWCS).

in general *work related risk factors* such as: lifting of loads, kneeling posture, prolonged standing posture, raised arms working posture, etc. (section C in Figure 7.1). For each type of risk factors, the most involved and overstressed muscles have been identified (section D in Figure 7.1). The muscles involved in each task are visible in Table 7.2.

Table 7.2: Muscles associated with work task.

Reference	Working task	Muscles
[117]–[121]	Repetitive Manual Handling	- Anterior Deltoid - Middle Deltoid - Trapezius - Biceps - Infraspinatus - Supraspinatus - Extensor Carpiradialis
[122]–[124]	Manual Lifting	- Lumbar Erector Spinae - Thoracic Erector Spinae - Multifidus - Rectus Abdominis - Internal Abdominal Oblique - External Abdominal Oblique - Latissimus Dorsi - Biceps Brachii - Triceps Brachii - Trapezius - Anterior Deltoid - Infraspinatus
[125]–[127]	Prolonged Standing Posture	- Lumbar Erector Spinae - Thoracis Erector Spinae - Multifidus - Tibialis Anterior - Gastrocnemius
[128], [129]	Prolonged Sitting Posture	- Lumbar Erector Spinae - Thoracis Erector Spinae - Rectus Abdominis - External Abdominal Oblique - Multifidus - Latissimus Dorsi

Continued on next page

Table 7.2 – *Continued from previous page*

References	**Working task**	**Muscles**
[130], [131]	Pushing and Pulling	- Pectoralis Major - Infraspinatus - Anterior Deltoid - Middle Deltoid - Posterior Deltoid - Supraspinatus - Upper Trapezius - Biceps Brachii - Triceps Brachii - Erector Spinae
[132], [133]	Squatting and Kneeling Posture	- Erector Spinae - Biceps Femoris - Rectus Femoris - Vastus Medialis - Vastus Lateralis - Semitendinosus - Gastroacnemius - Soleus
[117], [134], [135]	Arms above the shoulder's height	- Upper Trapezius - Deltoid - Infraspinatus

The muscles on which to place the textile electrodes to embed into the wearable device for the first prototype development, are selected among others according to specific design constraints dictated by the Design Team. The principal **design constraints** of the product are visible in Table 7.3. The design constraints led to the exclusion of the following muscles:

- Tibialis, Gastrocnemius, Semitendinosus and lower body muscles in general were excluded because the wearable is a shirt garment;
- Deltoid, Biceps, Triceps, Extensor Carpiradialis was excluded because the shirt is sleeveless.

Based on these constraints, essentials for the development and production of the device, the following 4 muscles on which to place the electrodes were chosen from those presented in Table 7.2:

- Upper Trapezius Right and Left;
- Infraspinatus Right and Left;
- Latissimus Dorsi Right and Left;
- Erector Spinae Right and Left.

Table 7.3: Design constraints.

Design constraint	**Implication**
8 channels sEMG system	8 Muscles selection
Symmetrical acquisition	8 Muscles (4 bilateral pairs)
Surface EMG	Deep muscles investigation is excluded
Sleeveless Shirt	Arm's muscles are excluded
Electrodes should be all placed on front or on back of the body due to the design of cables routing	Only back muscles are investigated

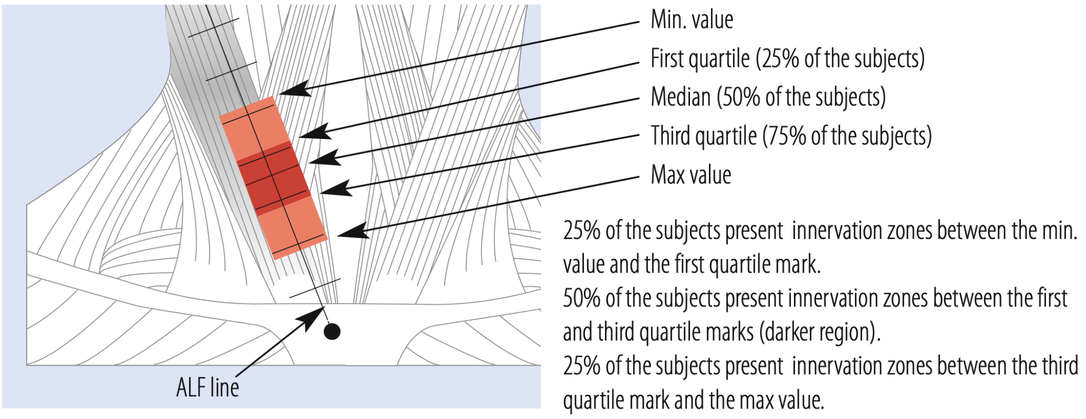
7.1.2. Electrodes Placement: Muscle Isolation tests

The LWT3 wearable device under development consists of a smart vest with textile sensors. The development of textile electrodes embedded in clothing, which do not require the careful placement of them for each subject, improves the ease of EMG measurement and potentially allow myoelectric activity patterns to be collected in previously inaccessible but more externally-valid settings, such as daily working environments [93].

In recent years, many efforts have been developed by manufacturers and researchers aiming to incorporate this technology in clothes [136]–[138] demonstrated close agreement with traditional surface EMG signals but since they do not allow a custom placement of the electrodes, as is done with disposable surface electrodes after locating the muscle, require specific tests to find the optimal electrodes placement and orientation. Considering also that the smart shirt is thought to be in different sizes, a perfect orientation is of paramount relevance contributing to the quality of the signal acquired. For this reason a series of *Muscle Isolation Tests* were conducted. These tests aim at isolating the activity of a target muscle with respect to adjacent muscles by performing a specific movement in a determined position. The starting point for muscle positioning is based on the *Atlas* published by *Barbero M., Merletti R. and Rainoldi A.* in 2012 [104] that shows the best area for electrode placement by studying the innervation zone of muscles. According to the authors [104], the best area for electrode placement is between the innervation area (IZ) and the distal / proximal tendon. By studying the positions of the IZ, whose distribution has been described by means of "box and whiskers plots", the areas of each muscle have been identified in which the probability that an innervation zone (IZ) is present is very high.

For each muscle investigated, the atlas provides the anatomical landmark frame (ALF) visible in Figure 7.2, which identifies the junction line between two anatomical landmarks, the area containing the distribution of the IZ described by the "box and whiskers plot" and the range in which the positioning of the electrodes is allowed, expressed as a percentage of the length of the ALF [104]. For the four bilateral selected muscles these ranges are shown in Table 7.4 and visible also in Figure 7.3.

Figure 7.2: Description of the innervation zone (IZ) in order to find the best area for electrode placement presented in [104].

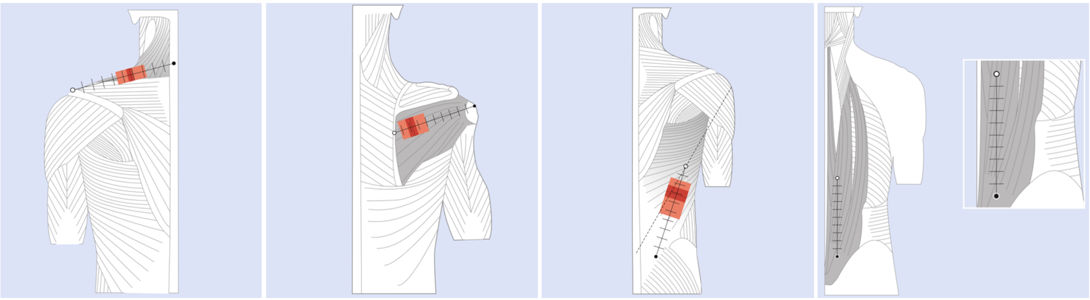


The best placement for bipolar electrode recording is the muscle area between the IZ and the distal/proximal tendon, the proper electrode placement can be determined by following the anatomical landmarks, avoiding the shaded red areas and, possibly, the “whiskers”.

For each muscle a series of tests with different positioning was conducted with the purpose of finding the optimal sites for the textile electrodes considering also that the smart shirt is thought to be produced in different sizes. It is necessary to find, rather than a precise site, an area in which the activity would be correctly recorded even if the electrode would be slightly displaced while worn by different subjects.

The tests were performed in isometric contraction of the muscle that was under testing and the minimization of the adjacent muscles contraction was investigated in order to reduce cross-talk as much as possible. Some exercises were arranged in combination with

Figure 7.3: Description of the innervation zone (IZ) in order to find the best area for electrode placement presented in [104].



From left to right: Upper Trapezius, Infraspinatus, Latissimus Dorsi, Erector Spinae.

manual resistance. Table 7.4 presents the selected sites as a starting point for electrode placement to carry out the tests. During the test sessions electrodes were repositioned close to those sites and the finding was an *area of placement* that was provided to the design team in order to develop the prototype.

The results of these experimental procedures and final positioning of textile electrodes cannot be provided in this study because they are reserved information the company explicitly asked to do not distribute externally. The following paragraphs describe the positions that the tester adopted and the isolating movements selected to perform the test sessions.

Upper Trapezius EMG electrodes were positioned bilaterally on Upper Trapezius (UT) and Infraspinatus (INF)in order to verify the muscular activity of Upper Trapezius and the possible cross talk from adjacent muscles. Surface EMG data was collected from the UT and INF muscles by two pairs of disposable Ag-AgCl electrodes. The electrodes were circular with conductive area of with 1 cm square each, placed with a centre-to-centre distance of 15 mm. The subject was seated with his arm abducted at 90°. An isometric contraction was then performed during elevation of the shoulders [104]. A static resistance was arranged by manually fixating the arm to press the shoulder down.

Infraspinatus Being the most important outward rotator of the shoulder cuff, the Infraspinatus muscle is best tested by externally rotating the upper arm with the elbows flexed at 90 degrees [103]. The elbows can either be at the subject's side or abducted 90 degrees to further isolate the Infraspinatus from the Upper Trapezius muscle. The subject conducted the excercise with unilateral manual resistance against the forearm. Surface EMG data was collected from the INF and UT muscles by two pairs of disposable Ag-

AgCl electrodes. The electrodes were circular with conductive area of with 1 cm square each, placed with a centre-to-centre distance of 15 mm.

Table 7.4: The data in the table shows the range in which the positioning of the electrodes is allowed, expressed as a percentage of the length of the Anatomical Landmark (ALF) (reported from [104]). Last column shows the starting sites chosen for the four bilateral electrodes placement.

Muscle	Starting point ALF	Ending point ALF	Optimal site	Selected starting site
Upper Trapezius	Clavicle	Spinal process of the sixth cervical vertebrae	Between 0% and 44% or between 72% and 100%	60%
Infraspinatus	Midpoint of the scapular medial border	Greater tubercle	Between 40% and 100%	50%
Latissimus Dorsi	Posterior superior iliac spine	Point between the greater tubercle and the spinal process of the fifth lumbar vertebrae	Between 0% and 16% or between 55% and 100%	10%
Erector Spinae	Spinal processes of the fifth lumbar vertebrae	Twelfth thoracic vertebrae	Throughout the ALF	30%

Latissimus Dorsi The Latissimus Dorsi (LD) is a very broad muscle and it contributes to shoulder adduction, internal rotation, and extension, and it directly connects the upper extremity and trunk. Because of its importance, researchers have investigated several exercise methods to activate the LD. Shoulder extension in the prone position is a widely used manual muscle test to independently activate the Latissimus Dorsi [139]. The participant lays prone on a bench with his arms by his sides and the shoulders internally rotated to create a palm-up position. From this position, the participant tried to move his shoulder toward the ceiling (extension). Downward manual resistance is applied to the forearm, and pressure is exerted on the contralateral side of the pelvis. Surface EMG data was collected from the Latissimus Dorsi and Erector Spinae muscles by two pairs of disposable Ag-AgCl electrodes. The electrodes were circular with conductive area of with 1 cm square each, placed with a centre-to-centre distance of 15 mm.

Erector Spinae The prone laying position on a bench is one of the most used position used for MVC test [103]. The patient lies prone on the examining table with the upper edge of the iliac crests in alignment with the edge of the table. The lower body is fixed to the table by three straps around the pelvis, knees, and ankles, respectively. With the arms folded across the chest, the patient isometrically maintains the upper body in a horizontal position. For the Erector Spinae is important to identify at which height of the vertebral column to place the electrodes considering the fit of the smart garment and its tightness to the body.

EMG signals were recorded continuously throughout the contraction-relaxation sessions for all four muscles. As concerns the signal processing; the raw sEMG signals were bandpass filtered between 20 and 500 Hz at 1000 Hz sampling frequency to remove the noise associated with biological and non-biological artefacts. The raw and filtered signals were plotted over the trial duration for each muscle separately and visually inspected to identify any abnormalities and assess whether the filters had successfully removed noise and artifacts.

7.2. Protocol Design Development

The protocol developed constitutes a method to acquire information about muscular activity during simulated working tasks execution in a laboratory environment exploiting sEMG and Motion Capture technologies with the purpose to identify the timing activation and deactivation patterns of target muscles related to the type of task being executed (pushing and pulling, work with arms above shoulder's height, repetitive of handling of low loads, etc.). The protocol was developed with the purpose to be used in next phases of WINGS (Wearable Industrial Gear) project to validate the Smart Garment prototype and for this reason the protocol after its definition needs to be validated before to be used to test the prototype. In this section will be discussed the protocol development steps (Section 7.2.1 and then its validation in Section 7.2.2 will follow.

Among the categories of methods for recording and assessment of physical risk exposure when performing specific working tasks, the laboratory measurements are the only that permit to replicate the processes under standardized experimental conditions and therefore yield the most precise data on the physical workload situation as already shown in Table 3.1.

7.2.1. Protocol Development

The protocol was developed as a form composed by several parts and implemented in python in order to be inserted directly in the acquisition app of LWT3 and to be filled when registering the subjects. The protocol is composed by the following parts:

- Subjects information;
- Environment conditions;
- Working task;
- sEMG and Motion Capture technologies;
- Electrodes placement;
- Markers placement.

In Section 7.1.1 the sectors and related working tasks that mainly report injuries and MSDs pathologies were identified. In this study in order to validate the developed Protocol the *Repetitive Manual Handling* task was selected as a case study, among all the job tasks identified. The Experimental Procedures conducted (Section 7.2.2) represent therefore an application of the Protocol on a specific working task, future implementations include further working tasks investigation.

Subjects Data Collection

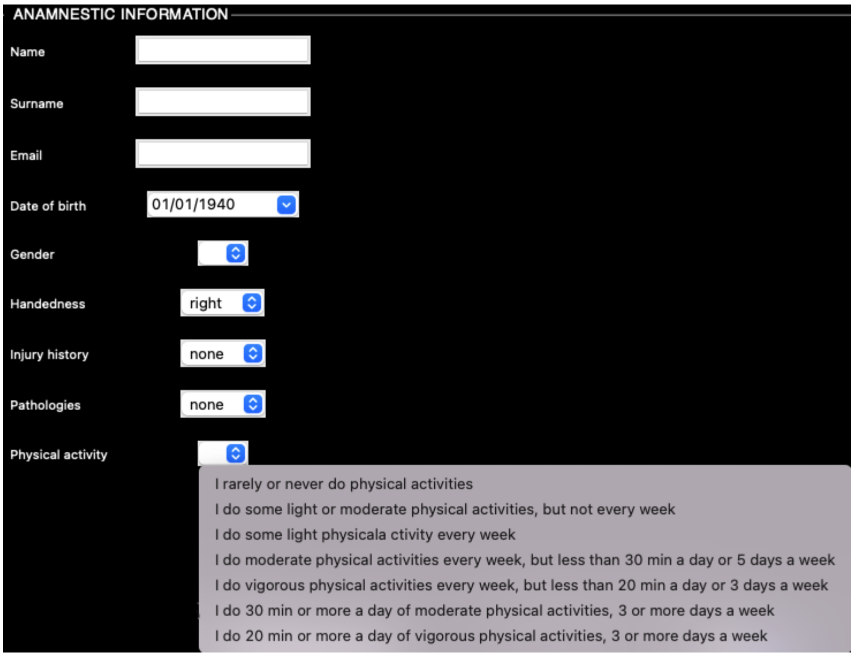
The first part of the Protocol regards the subjects information:

- Anamnestic information (see Figure 7.4);
- Rapid physical assessment in order to know the physical conditions of subjects (see Figure 7.4);
- Anthropometric measurements necessary for the positioning of the standard electrodes (distance between anatomical points of interest) and for the cinematic acquisitions (7.5).

Environment Conditions

The second part of the form (visible in Figure 7.6) concerns the environment conditions which are very important when working. Occupational risk factors for heat illness include heavy physical activity, warm or hot environmental conditions, lack of acclimatization, and wearing clothing that holds in body heat [140]. Hazardous heat exposure can occur indoors or outdoors, and can occur during any season if the conditions are right, not only during heat waves that's why is important to assess and specify also the environment conditions during which the test is performed when simulating a working task.

Figure 7.4: Subjects information form: anamnestic information and physical activity.



ANAMNESTIC INFORMATION

Name
Surname
Email
Date of birth 01/01/1940
Gender
Handedness right
Injury history none
Pathologies none
Physical activity

- I rarely or never do physical activities
- I do some light or moderate physical activities, but not every week
- I do some light physicala ctivity every week
- I do moderate physical activities every week, but less than 30 min a day or 5 days a week
- I do vigorous physical activities every week, but less than 20 min a day or 3 days a week
- I do 30 min or more a day of moderate physical activities, 3 or more days a week
- I do 20 min or more a day of vigorous physical activities, 3 or more days a week

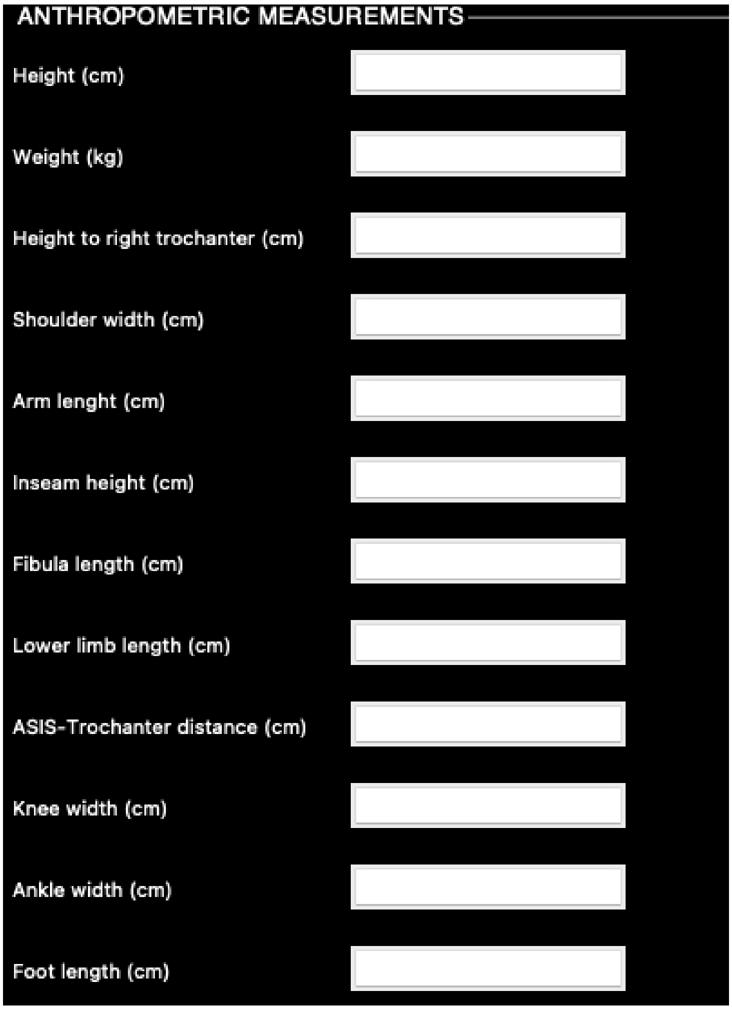
Task and Test Site

This part of the Protocol concerns the Setup and *Working Task* definition. Whereas the previous parts of the Protocol are task independent, here the parameters selected are task-based and the test site is defined in relation with the movements selected to simulate the working task (Figure 7.7). Future applications of the Protocol will see this part adapted to the task which is object of study.

The task simulated concerns a repetitive working activity performed by a cashier or worker involved in assembly line activities. The risk factors present in the activity that involves repeated movements and efforts on the upper limb are linked above all to the frequency of the actions, work organization (understood as the distribution of tasks and workload, interruptions, and breaks) and the adaptation of the worker to the work task demands [15]. As introduced in Section 3.2.2 the risk assessment requires the identification and quantification of many risk factors: frequency of actions, awkward postures of the upper limbs and lack of postural variation, exertion of force and inadequate recovery periods. The risk could also be enhanced by the presence of additional factors such as machine-paced work.

The test site was set up in LWT3 Laboratory and consists of a 87 cm height workbench. With respect to the physical design of an industrial workstation one of the most important design dimensions is the workstation height [141]. The International Standard 14738:2002 [142] specifies the body's space requirements and workstation height during normal oper-

Figure 7.5: Subjects information form: anthropometric measurements.



ANTHROPOMETRIC MEASUREMENTS

Height (cm)

Weight (kg)

Height to right trochanter (cm)

Shoulder width (cm)

Arm lenght (cm)

Inseam height (cm)

Fibula length (cm)

Lower limb length (cm)

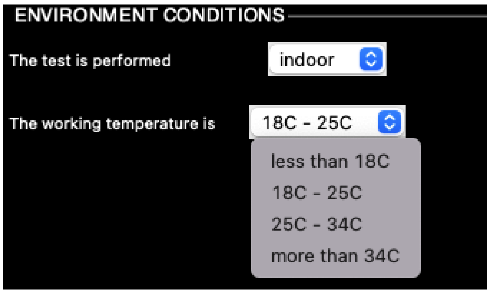
ASIS-Trochanter distance (cm)

Knee width (cm)

Ankle width (cm)

Foot length (cm)

Figure 7.6: Environment conditions parameters.



ENVIRONMENT CONDITIONS

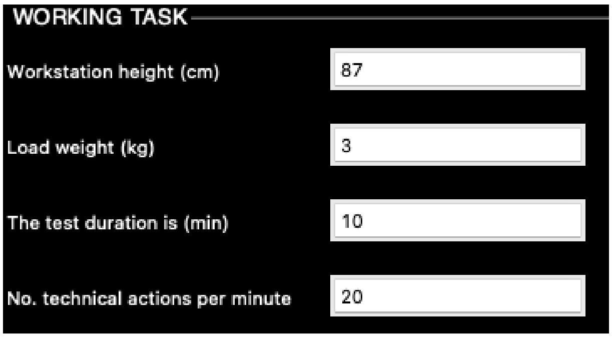
The test is performed: indoor

The working temperature is: 18C - 25C

ation in sitting and standing positions and the height of the table selected for this study comply with the Standard. The subject is standing up in front of the workstation and the task activity consists of the iterative handling of a 3 kg load with both arms between 2 marked positions on the workbench (Figure 7.8) for 10 minutes.

The task simulated in this study is classified by the Occupational safety and Health

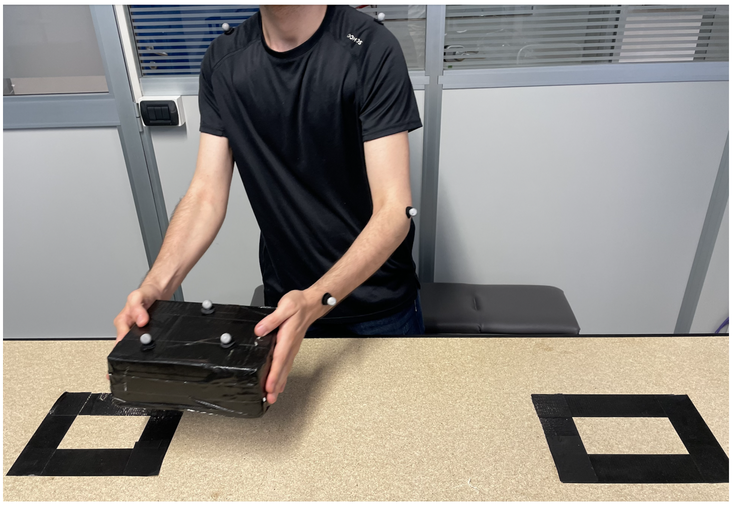
Figure 7.7: Working task parameters in the form.



WORKING TASK

Workstation height (cm)	87
Load weight (kg)	3
The test duration is (min)	10
No. technical actions per minute	20

Figure 7.8: Workbench with position A (on the left of the subject) and position B (on the right of the subject).



Directives (OSH) as *Manual Handling of Low Loads at High Frequency* and the parameters selected to create the protocol (e.g. frequency, duration and workstation set up) are settled on the basis of the OCRA method (described in Section 3.1.2), in particular the purpose was to perform a task that would be classified as acceptable when applying OCRA risk assessment method i.e. task with no exposure to risks. One of the main exposure to risk in this type of task is the number of technical actions per minute. The *technical action* is the elementary manual action required to complete an operation (i.e. the action of gripping, positioning an object in a pre-established point, pushing a button etc.).

The exact movements and timing to perform the task are the following:

1. Palmar grasp of the load and transfer of the last one from position A to position B in 1.5 sec.
2. Resting: 9 sec.
3. Palmar grasp of the load and transfer of the last one from position B to A in 1.5

sec.

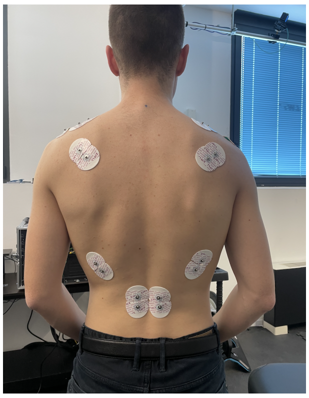
4. Resting: 9 sec.
5. Repeat from 1.

During the entire execution of the movement the subject is asked to watch a video tutorial in order to obtain a task as regular as possible in terms of the timing of the load handling and this option ensured a more uniform intra and inter-subject speed.

Electrodes Placement

The muscles considered in the study were selected according to a literature research and design constraints. The workflow of muscle selection is presented in Section 7.1.1.

Figure 7.9: Electrodes placement.



The electrodes positions are the same used as starting position to perform the **Muscle Isolation Tests** already described in Section 7.1.2. The electrodes placements are visible in figure 7.9. EMG electrodes were positioned bilaterally on Upper Trapezius, Infraspinatus, Latissimus Dorsi and Erector Spinae. Each pair of electrodes was placed parallel to the muscle fibers and at an interelectrode distance equal to 10 mm.

Markers Placement

In this study, an optoelelectronic movement analysis system was used and 19 markers were placed on each subject at the anatomical landmarks shown in Figure 7.10 and as described in Table 7.5; 3 further markers was placed on the load to be identified by the system as a rigid body.

Figure 7.10: Markers placement.

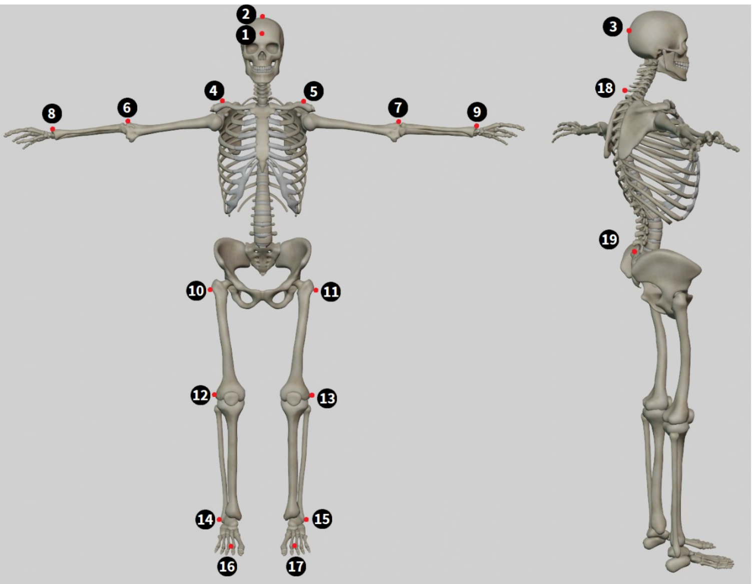


Table 7.5: Markers placement positions.

HEAD	**WRISTS**	**ANKLES**
1. Front of the head	8. Right Ulnar Styloid Process	14. Right Lateral Malleolus
2. Top of the head	9. Left Ulnar Styloid Process	15. Left Lateral Malleolus
3. Back of the head		
SHOULDERS	**PELVIS**	**FEET**
4. Right Acromion	10. Right Greater Trochanter	16. Right 2nd Metatarsophalangeal Joint
5. Left Acromion	11. Left Greater Trochanter	17. Left 2nd Metatarsophalangeal Joint
ELBOWS	**KNEES**	**BACK**
6. Right Humerus Lateral Epicondyle	12. Right Femur Lateral Epicondyle	18. C7 vertebrae.
7. Left Humerus Lateral Epicondyle	13. Left Femur Lateral Epicondyle	19. Top of Sacrum near the S2 vertebrae

7.2.2. Protocol Validation: Experimental Procedures

The experimental procedures conducted in this study represent the validation of the Protocol discussed in Section 7.2.1 on a specific working task: manual handling of low loads at high frequency. Future implementations include further working task investigation such as lifting of loads, pushing and pulling activities, squatting and kneeling working posture, etc. (see Table 7.2) with the purpose to identify the activation and deactivation patterns in muscles groups by type of task.

The experimental procedures were performed at LWT3 Laboratory and is composed by several sub-phases described in the following sections.

Calibration of the Optoelectronic System

The position of the cameras is defined to allow the optoelectronic system to acquire the coordinates of the markers. The 6 cameras available are positioned in the laboratory in order to capture the entire test site. To allow the measurement of the three-dimensional coordinates of the center of each marker, it is necessary that at least a couple of cameras sees each marker. Thus, the cameras must be positioned accordingly, and it is important to verify that the markers are not "lost" or hidden by other parts of the body during the acquisition. Once the cameras are placed in order to acquire correctly all the markers positioned on the body the calibration of the optoelectronic system is performed. The calibration process was carried out in two successive phases using the Motive Optical Motion Capture software:

1. Wand Sequence permits to define the volume of work, acquiring the movement, for a determined time interval, of a bar on which 3 markers are positioned at a known distance;
2. Ground definition involves the placement on the ground and the registration of the Ground Tool (visible in Figure 7.11), on which 3 markers are positioned at a known distance, which defines the reference system of the laboratory.

Figure 7.11: Optitrack Calibration tools [115].

(a) Wand.

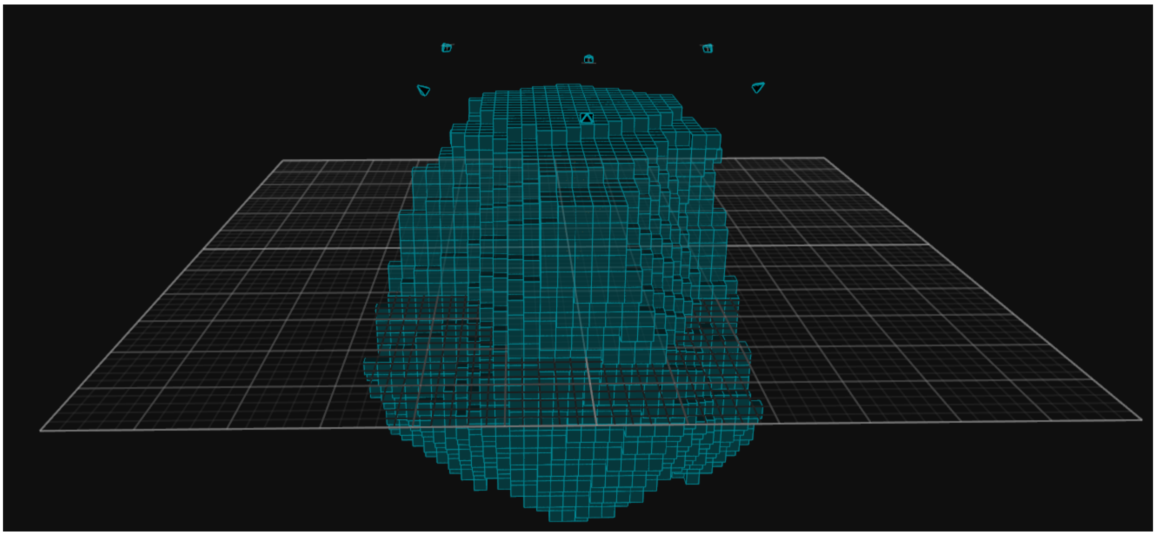
(b) Ground tool

This procedure allows defining the calibration volume (visible in Figure 7.13) and the absolute Cartesian reference system (origin and orientation of the axes in the laboratory) and determines the internal parameters (focal length, coordinates of the main point and distortion coefficients) and external (position of the system of camera reference with respect to the absolute reference system) of the cameras. Each day, a new calibration is performed.

Subjects Preparation and Registration

Eight healthy subjects (4 males and 4 females) voluntarily participated in the study. All subjects gave their informed consent before the experimental session. Anthropometric

Figure 7.13: Calibration volume.



measurements were carried out for each of them, necessary for the positioning of the standard electrodes (distance between anatomical points of interest) and for the cinematic acquisitions.

Table 7.6: Characteristics of the participants (mean + standard deviation).

Age (Years)	**Body Mass (kg)**	**Height (cm)**
24.13 ±2.36	60.87±11.9	165.63±6.98

Before starting the test, each subject was explained in detail the type of movement to be performed and the methods. In order to guarantee the most possible replicability and uniformity it was decided to use a tutorial that would guide the participants during the entire execution of the task.

The anamnestic information and anthropometric measurements of interest were registered through the form implemented in the LWT3 application shown in Section 7.2. The electrodes were placed according to the established positioning, defined in Section 7.1.2 and visible in Table 7.4. The clip electrodes were then applied to which the EMG board were connected. Finally, the 22 markers were applied according to the previously described protocol (see Table 7.5). Figure 7.9 shows the arrangement of the electrodes and markers on subject.

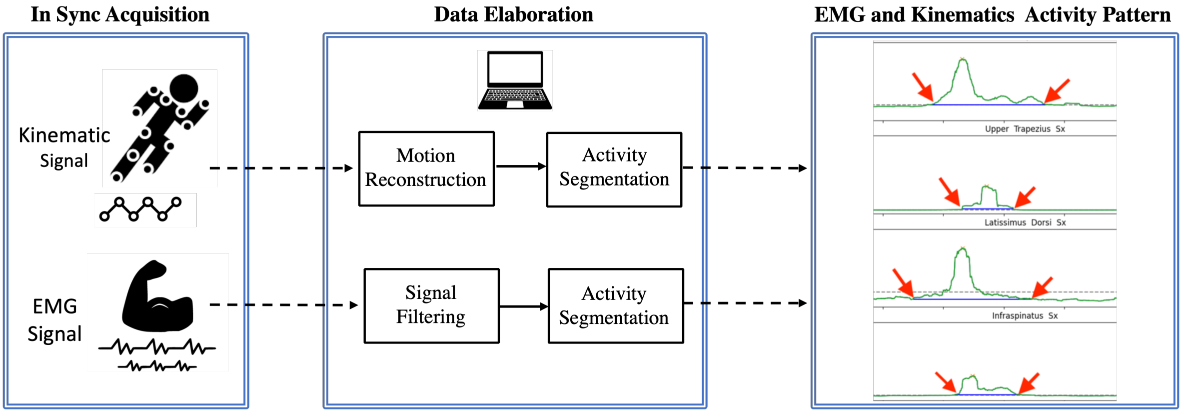
Kinematic and sEMG acquisition

Once the subject is placed inside the calibration volume in front of the table, a final tuning before to acquire the kinematic and sEMG signal was performed in order to check that the EMG signal is not affected by disturbances or noise and that the subject is correctly recognized by the optoelectronic system. The type of movement to be performed and the method of execution are then explained to the subject. We then proceeded to the acquisition phase of the electromyographic (at the sampling frequency of 1000 Hz) and kinematic signals (at the sampling frequency of 120 Hz) using the Motive Motion Capture software. To initialize the software and determine the baseline estimate of the body segments positions and orientations, a recognition procedure must be performed, which involves the subject standing in an upright posture with arms in "T position" for a few seconds.

7.2.3. Data Analysis

sEMG and kinematic data were processed using Python version 3.10. The flow chart of Kinematics and EMG data flowing and processing is shown in Figure 7.14. The following two sections present the data elaboration for EMG and kinematic signals.

Figure 7.14: Flow chart of kinematics and EMG data processing.



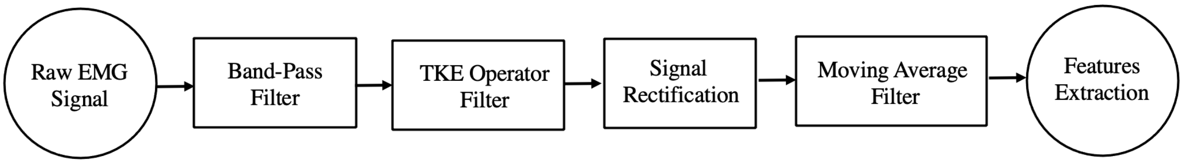
sEMG Signal Processing

The electromyographic signals are processed and filtered to obtain an envelope of the signal of all 8 muscles then a detection algorithm is defined in order to identify the onset and offset timing of muscles for all displacements of the load during the 10-minute trial.

The processing steps are as follows. The raw sEMG signal was bandpass filtered between 20 and 500 Hz at 1000 Hz sampling frequency to remove the noise associated with biological and non biological artefacts.

The raw and filtered signals were plotted over the trial duration for each muscle separately and visually inspected to identify any abnormalities and assess whether the filters had

Figure 7.15: sEMG signal processing and filtering flow chart from raw EMG signal to features extraction.



successfully removed noise and artifacts. If any artifacts or signal quality issues were identified, the data for the specific muscle was discarded, while the data for the remaining muscles were included in the analysis.

Then the Teager–Kaiser Energy Operator (TKE) filtering was applied in order to increase the accuracy of the electromyography onset detection method defined and applied afterwards. The non-linear TKE Operator, introduced by Kaiser [143], measures instantaneous energy changes of signals composed of a single time-varying frequency. TKE Operator improves the ability to analyze muscle activity, emphasizes both properties of motor unit action potentials, amplitude and frequency, whereby onset detection becomes more accurate [144].

The TKE Operator gives a transformed signal $y(n)$, as follows:

$$y(n) = x^2(n) - x(n+1)x(n-1)$$

where $x(n)$ is the EMG and n is the sample number.

Then the signal was full-wave rectified and smoothed using a 500 ms mean window. To identify the onset and offset muscle activity a detection algorithm was defined. First the peaks of the envelope of the signal above a certain threshold (thr), within a window of 9000 samples, was identified (see Figure 7.17). The resting time between two consecutive displacements of the load is 9 seconds, defined by the acquisition protocol described in Section 7.2.1, and this permits to define the algorithm so as to identify one peak every 9 seconds at most.

The threshold thr (dashed gray line in Figure 7.18) was defined as:

$$thr = \mu + J\delta$$

where μ and δ are the mean and standard deviation of the envelope during a period of inactivity, and J is set to 6 (after testing different possible values of J).

Figure 7.16: The Figure shows the filtered EMG signal. Up: signal bandpass filtered between 20 and 500 Hz at 1000 Hz sampling. Down: signal after TKE Operator, full-wave rectification and smoothing application.

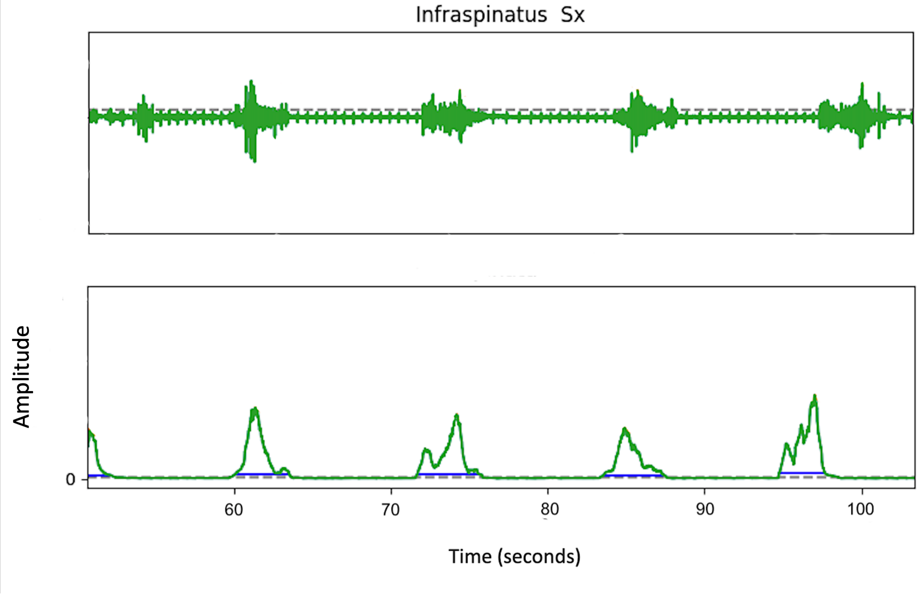
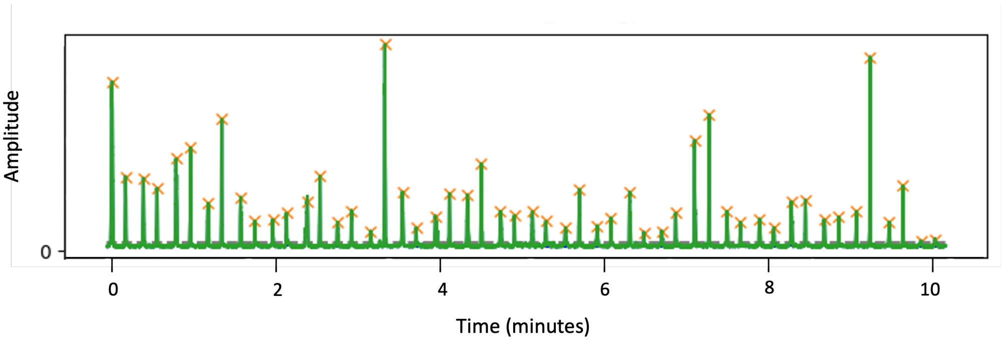


Figure 7.17: Algorithm applied to identify peaks corresponding to maximum activity for all cycles that corresponds to the load displacements executed during the trial.



Once the peaks are found, the prominence of each peak is identified. The prominence of a peak measures how much a peak stands out from the surrounding baseline of the signal and is defined as the vertical distance between the peak and its lowest contour line. Therefore a horizontal line (blue line in Figure 7.18) is delineated representing the muscle activity period.

The onset and offset muscle activity time instants are then identified and extracted for all the eight muscles as shown in Figure 7.19 and plotted as in Figure 7.20 where is illustrated sequence of onset and offset muscular activity registered during a cycle which is defined by a load displacement.

Figure 7.18: The threshold *thr* is represented by the dashed grey line.

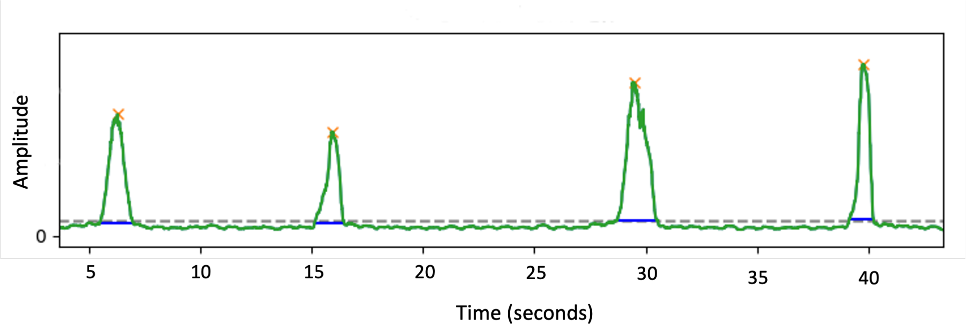
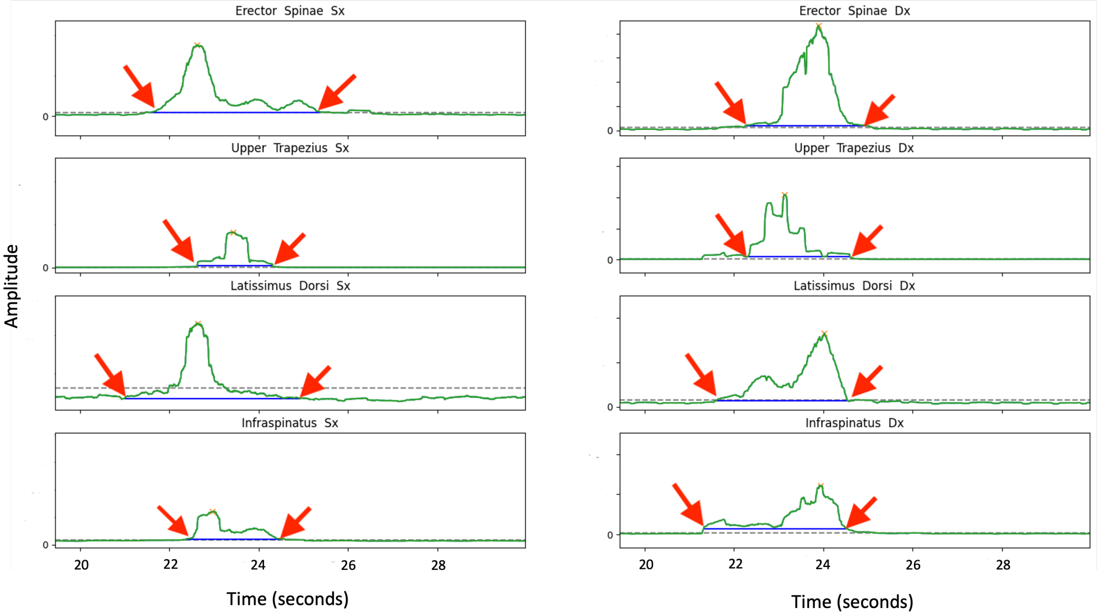


Figure 7.19: The onset and offset muscle activity time instants are identified and extracted for all the eight muscles and for all the activity cycles. A cycle is represented by a load displacement and in this figure is shown an example of identification of activation and deactivation time instants of the eight muscle for the same cycle.

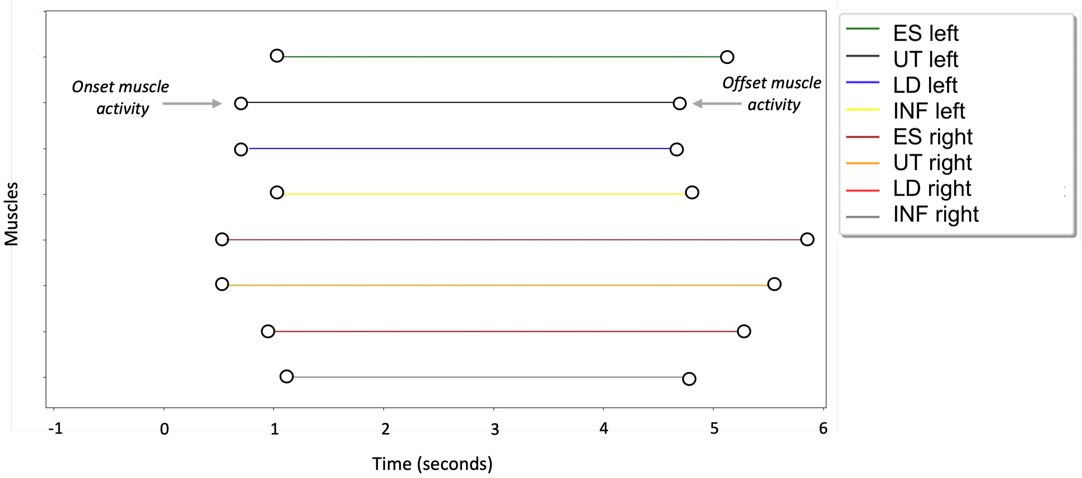


Kinematic Data Processing

Kinematic data were processed without any smoothing or filtering. The information from the marker positioned on the load are used to trace the displacement of the load during the trial. Specifically, the position on vertical axes was taken as a reference and the kinematic data was segmented in order to identify the beginning and end of each displacement of the load.

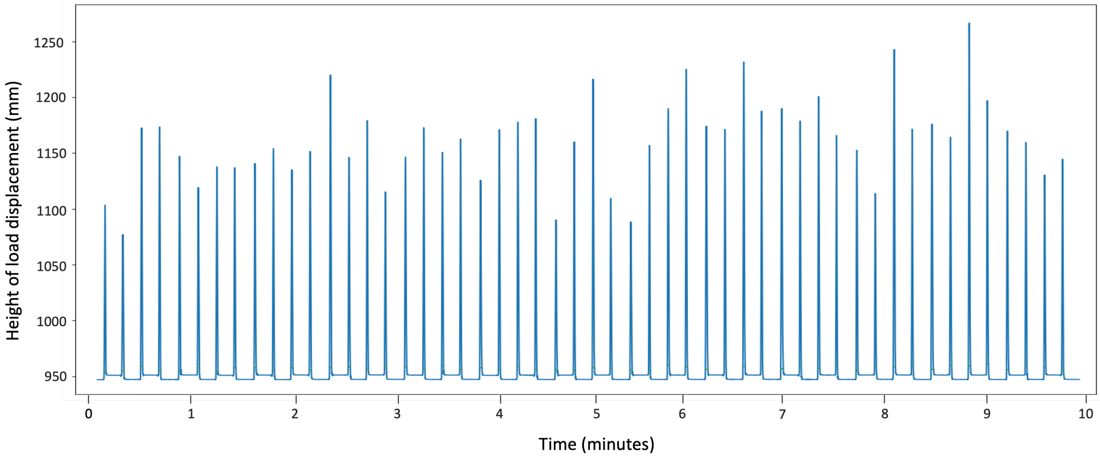
Load trajectory on vertical axis during a 10-minute trial is visible in Figure 7.21 and it serves to correlate the muscle activity to the *lifting* and *releasing* time instants of the load

Figure 7.20: Sequence of muscular activity duration registered during a load displacement. From top to bottom: Left Erector Spinae, Left Upper Trapezius, Left Latissimus Dorsi, Left Infraspinatus, Right Erector Spinae, Right Upper Trapezius, Right Latissimus Dorsi, Right Infraspinatus.



in each displacement. The two events are categorized as initial and final event of the load displacement as shown in Figure 7.22.

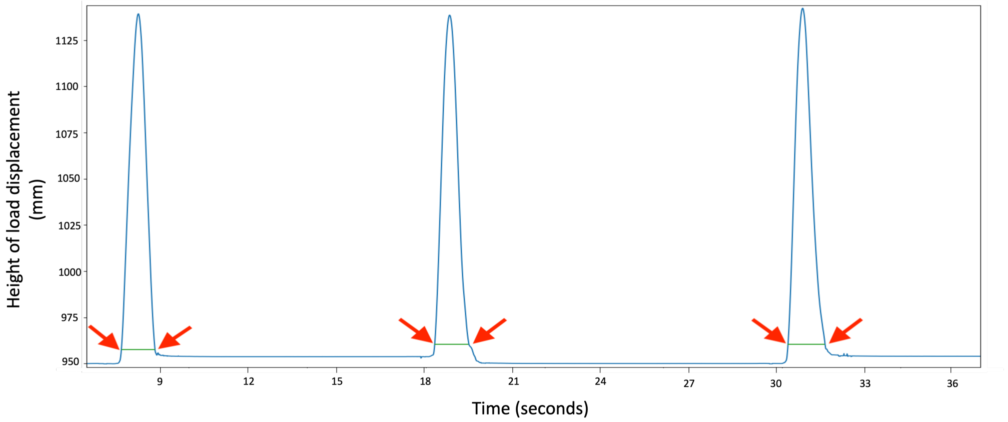
Figure 7.21: Load trajectory on vertical axis during a 10-minute trial. The *height of the load displacement* refers to height at which the load is moved during the trial. The starting height is 950 mm because the load is placed on the workdesk which is 870 mm high and the load is 80 mm high.



The kinematic and EMG information elaborated and extracted as mentioned above are plotted in Figure 7.23 where the two vertical lines represents the time instants the load is lifted and released by the subject and the horizontal lines are the activity duration of the eight muscles.

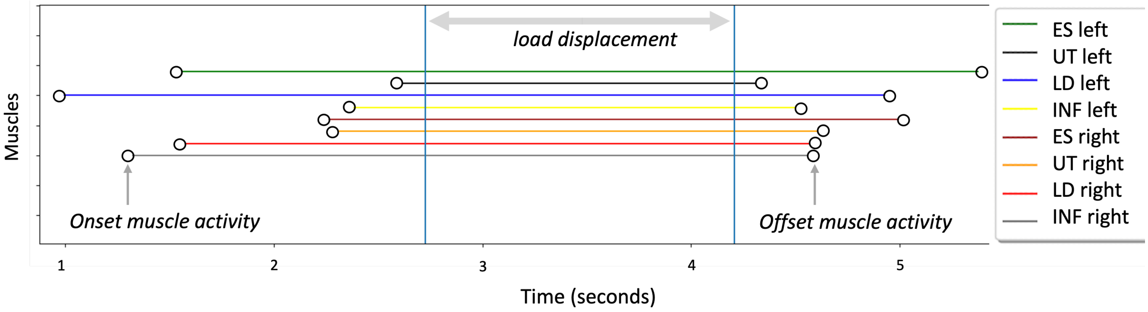
This duration is intended as a total duration as it includes the activity registered from

Figure 7.22: The graph represents the load trajectory on the vertical axis and the identification of the time instants in which the load is lifted and realised by the subject during the trial. The two events are extracted for each load displacement during the 10-minute trial.



the onset muscle time instant to the offset time instant. As concerns kinematics, we have the decomposition of the load displacement into three phases: the initial *reach* phase, the *hold* phase while the load is being transported and the *releasing down* phase of the load.

Figure 7.23: The figure represents the muscle activity pattern during a load displacement cycle. The two blue vertical lines represent the time instants the load is *lifted up* and *released down* respectively. The horizontal lines represents the activity duration of the eight muscles with the onset and offset time instants represented by the circles.



8 | Results and Discussion

The results obtained in this study are of multiple nature. The first result obtained regards the muscles selection to be embed into the wearable device in order to design and develop the first prototype. The systematic research about the MSDs, their prevalence and the risk factors associated to working task such working in awkward positions, heavy physical work, lifting, repetitive work, prolonged computer work, among others, permitted to select the muscles that are mainly overstrained and fatigued and that need to be monitored. Based on the design constraints, essentials for the development and production of the smart garment, the bilateral muscles on which to place the electrodes are Upper Trapezius (UT), Infraspinatus (INF), Latissimus Dorsi (LD) and Erector Spinae (ES).

Considering then that a perfect fit and positioning is of paramount relevance in this kind of smart garment, the contact, stability, and positioning of electrodes on the user's skin need to be correctly placed according to a certain orientation on the muscle fibers. Muscle Isolation Tests were performed for this purpose and permitted to obtain the textile electrodes positioning area and their orientation. The final results of these experimental procedures cannot be provide in this study because they are reserved information that the company explicitly asked not to distribute externally.

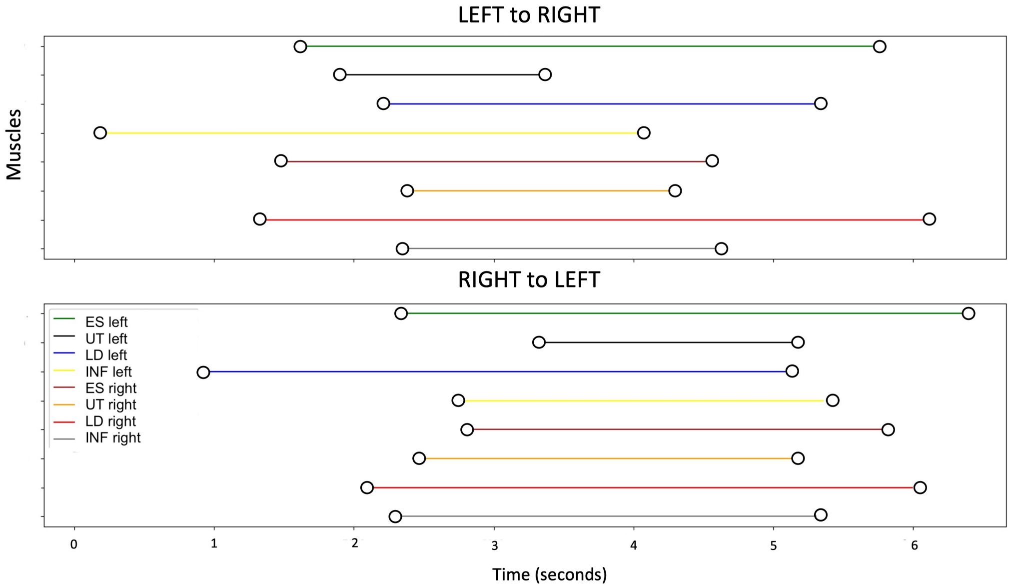
In the Work related injuries prevention context, the WINGS engine needs to be trained to discern the wrong movements from the correct ones. Wrong movements refer to tasks and working activities that potentially lead to develop musculoskeletal disorders if carried out wrongly for a long time. The system allows to warn the operator of possible dangers to his health, in real time and/or on a long-term thanks to a particular batch analysis. In order to allow this type of inference, it was necessary to define a systematic and replicable methodology that permits to LWT3 to simulate different working task in a laboratory environment aiming at gathering correct muscular activation and deactivation patterns using sEMG and MOCAP technologies.

The protocol developed permits to acquire different types of working tasks since it represents a systematic method to acquire and elaborate data following a certain procedure: same technologies, same target muscles, subject preparation and setup. The protocol developed permits then to acquire reliable EMG and kinematic data, import them in the client Database and perform automatic filtering and processing in order to extract patterns about muscle activity during specific tasks performance.

Among the working activities targeted with the main risk factors for WR-MSD, it was selected a task that can be easily executed, simulated and implemented in a laboratory environment in order to validate the protocol and extrapolate the muscle activity patterns with the purpose to exploit the protocol for future experimental procedures and to test the garment prototype when ready.

The patterns extrapolated and shown in Section 7.2.3 are defined for each load displacement cycle performed during the 10-minutes trial and for all subjects. The task executed is symmetrical with respect to the sagittal plane and in order to define the distribution of the muscles activity of subjects for the eight muscles the dataset was splitted in two sets: one considers the displacements of the load from left to right only and the second those from right to left, as visible in Figure 8.1.

Figure 8.1: Sequence of muscular activity duration registered during a load displacement. From top to bottom: Left ES, Left UT, Left LD, Left INF, Right ES, Right UT, Right LD, Right INF. The pattern on the top represents the activity during the displacements of the load from left to right subject's side and on the bottom those from right to left.



The number of cycles identified by the algorithm is compared with the number of actual cycles performed by each subject. If any artifacts or signal quality issues were identified, the data for the specific muscle was discarded, while the data for the remaining muscles were included in the analysis. The total accuracy is computed as:

$$Accuracy\,\% = \frac{Number\ of\ cycles\ identified}{Actual\ number\ of\ cycles} * 100 \tag{8.1}$$

where a cycle is considered correctly identified when the muscle activity is well segmented by the system. The results are reported in Table 8.1.

Table 8.1: Accuracy of the EMG activity detection algorithm.

	Accuracy %	**Muscles discarded**
Subject 1	98,5%	None
Subject 3	98%	None
Subject 6	94%	None
Subject 2	95%	1
Subject 4	89%	1
Subject 5	83%	2
Subject 7	81%	2
Subject 8	92,5%	2
Total	91,37%	

In Ergonomics, sEMG allows the user to quickly analyze the neuromuscular effort spent performing certain activities and instantly evaluate the intensity of work tasks. While performing tasks that involve a low muscle effort, i.e. low EMG amplitude values, identify the resting periods and for how long the muscle remains in contraction to execute the task (continuous activation state) is relevant and may be a starting point to understand if the task is correctly executed.

Figure 8.2: ES left activity durations during activity cycles.

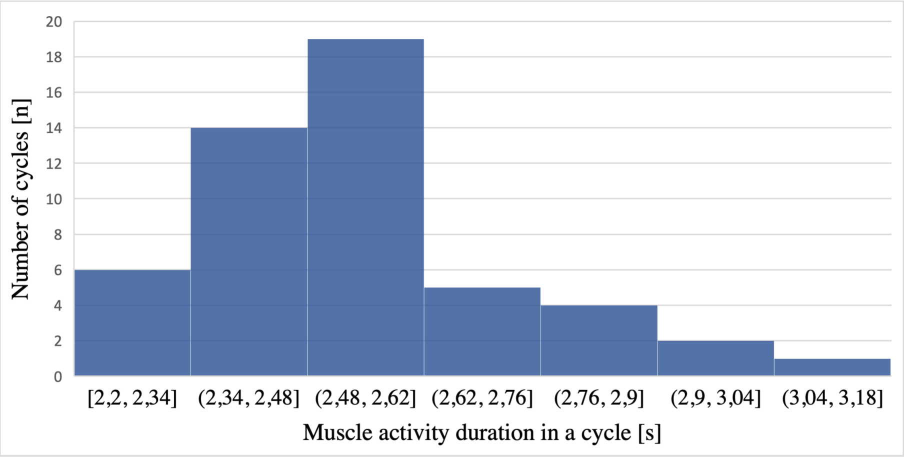
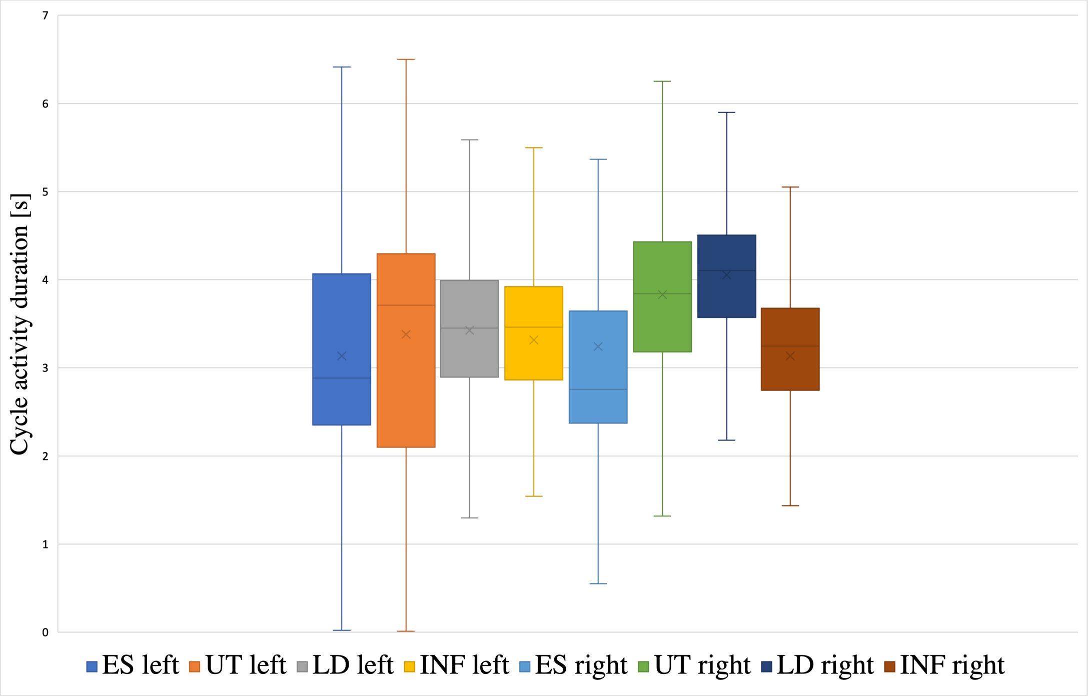


Figure 8.2 shows the activity durations of left Erector Spinae during cycles. When comparing different records of the same task, any shift of the distribution to the left indicates an economical effect because the muscle works less to perform the same task i.e. the duration in which the muscle remains continuously active is shorter, and therefore the muscle is less fatigued over time.

Figure 8.3: The figure shows the inter-subject variability of the muscle activity duration during cycles. Medians (solid line), means (cross) and interquartile ranges.

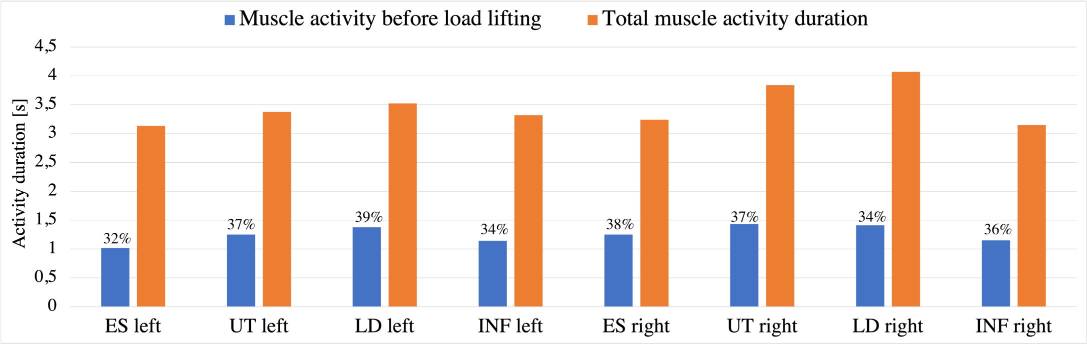


In order to assess the repeatability of the task execution the inter-subject variability of the muscles activation during cycles were analyzed. Results are shown in Figure 8.3. It can be seen that the maximum variability in duration is found in the UT left and the minimum in the LD right.

In a load displacement cycle, in addition to the muscle activity due to the actual displacement of the load, i.e. the *hold* phase, there is also an anticipatory muscle activity in which the muscle is already activated and this phase is represented by the *reaching* phase, the muscle activity registered during the reaching and gripping of the load. The Figure 8.4 shows the duration of the muscle activity during the reaching phase expressed as a percentage of the total muscle activity and it varies between 32% and 39%.

The kinematic information is also important because it can allow to assess how the movement is performed in order to see not only the activation of muscles with respect to the instant when the load is gripped but also to monitor the trajectory of the load during the

Figure 8.4: In orange: the average of the muscle activity duration of a displacement. This duration is intended as a total duration as it includes the activity registered from the onset muscle time instant to the offset time instant and it comprise the activity registered during the *reaching*, the *holding* and the *releasing down* phase. In blue: the duration of the muscle activity corresponding to reaching and gripping phase of the load, represented as a percentage of the total duration.



task. It need to take into account also the height at which the load is moved by subjects. Table 8.2 shows the mean height of displacement during cycles by subject.

The high variability of EMG data reflects also the variability of kinematic information, must take also into account the differences between subjects and how they use in average to move the load. The Standard deviation of height of load displacement is found to be high and also considering the limits represented by the small sample size these results can be integrated into a wider evaluation and a starting point to create a dataset of movements that the system would classify as correct.

Table 8.2: Mean height with which the load was displaced during the trial by participant.

	Height (mm)
Subject 1	214,8
Subject 2	203,06
Subject 3	67,09
Subject 4	59,12
Subject 5	94,43
Subject 6	186,96
Subject 7	55,14
Subject 8	59,86
Mean (±SD)	117,57 (±71,03)

9 | Conclusions

The work presented in this study is part of the development of WINGS device; a smart garment for online ergonomic assessment and posture biofeedback in the context of WR-MSDs prevention.

My contribution to LWT3 project was based on a double frontier. In order to design and develop the first prototype of the smart vest, I supported the design team in selecting the muscles on which to place the textile electrodes. The bilateral four muscles selected is the result of a deep literature research in terms of correlation between the main Musculoskeletal Disorders in work environment, sectors that are mainly affect by MSDs absenteeism and the working activities associated to those working sectors. These were established also considering the design constraints dictated by the company.

Previous studies using textile electrodes embedded in garments have demonstrated close agreement with traditional surface EMG signals but since they do not allow a custom placement of the electrodes, as is done with disposable surface electrodes after locating the muscle, require specific tests to find the optimal electrodes placement and orientation. Considering also that the smart shirt is thought to be in different sizes, a perfect orientation is of paramount relevance contributing to the quality of the signal acquired. For this reason a series of *Muscle Isolation Tests* were conducted.

These tests aimed at isolating the activity of a target muscle with respect to adjacent muscles by performing a specific movement in a determined position. The starting point for muscle positioning is from the *Atlas* published by *Barbero M., Merletti R. and Rainoldi A.* in 2012 that shows the best area for electrode placement by studying the innervation zone of muscles. For each muscle was conducted a series of tests with different positioning with the purpose to find the optimal sites for the textile electrodes considering also that the smart shirt is thought to be in different sizes, it was necessary to find, rather than a precise position, an area in which the activity would be correctly recorded even if the electrode would be slightly displaced.

WINGS engine need to be trained in order to discern the wrong movements from the correct ones, to assess in real time the working activities. The second part of my work concerned the definition of an Acquisition Protocol that aims at simulating different working task, such as lifting of loads, handling of low loads at high frequency, pushing and pulling, work in prolonged standing posture, etc. The protocol was developed as a form composed by several parts and implemented in python in order to be inserted directly in the acquisition app of LWT3 and to be filled when registering the subjects. The protocol was created in view of this purpose: gather correct task based muscular activity patterns using sEMG and MOCAP technologies in order to be trained and be able then to assess if postures or working movements/cycles are correct or not and provide corrections.

The experimental procedures conducted in the LWT3 Laboratory represents the simulation of workers engaged in repetitive manual handling of loads that constitutes one of the main risk factors for WR-MSD. The sample was composed by 8 subjects and it served as a sample to define the data analysis and elaboration to perform in order to extract correct patterns of muscle activation. I thus focused on the acquisition, processing and design and implementation of a surface myoelectric signal analysis system searching for the best sEMG signal processing technique, among different methods chosen from those which presented the best results in the literature. The algorithm implemented permitted to extrapolate the patterns of activation and deactivation cycles during the 10-minute trial. The accuracy of the detection method used permits to identify more than 91% of cycles but this result is obtained by discarding a series of muscles from the evaluation due to artifacts or signal quality issues.

It can therefore be said that, although the entire project has not yet reached its completion, the advances introduced by this study have made it possible to design the first prototype and to determine a systematic methodology that will be used by the company to conduct future procedures and tests for the smart garment validation phase.

As concerns thus the future implementations, the next experimental procedures will focus on the smart shirt prototype when ready, in order to assess the quality of the textile electrodes embedded by performing the same task performed in this study and a statistical comparison will follow.

Then a series of acquisitions, applying the protocol developed, will be conducted and more specifically the acquisitions will be done by registering different working activities in order to register as many correct patterns as possible in order to train the system to classify everyday working tasks as correct or incorrect.

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