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An experimental approach for the characterization of prolonged sitting postures using pressure sensitive mats

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An experimental approach for the characterization of prolonged sitting postures using pressure sensitive mats

A dissertation
submitted to the PhD School in Industrial Engineering
in partial fulfillment of the requirements
for the degree of
Doctor of Philosophy

Federico Arippa

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Abstract

The adoption of prolonged sitting posture, which is a condition commonly encountered in several working tasks, is known to induce a wide range of negative effects, including discomfort, which has been recognized as an early predictor for musculoskeletal disorders (particularly low back pain). In this regard, the continuous monitoring of worker's psychophysical state while sitting for long periods of time, may result useful in to preventing and managing potentially risky situations and to promote ergonomics and macroergonomics interventions, aimed to better organize work shifts and workplaces. The aim of this dissertation is to provide and test the reliability of a set of monitoring parameters, based on the use of quantitative information derived from body-seat contact pressure sensors. In particular, the study was focused on the assessment of trunk postural sway (the small oscillations resulting from the stabilization control system) and the number of In Chair Movements (ICM) or postural shifts performed while sitting, proven as a reliable tool for discomfort prediction.

This thesis is articulated into four experimental campaigns. The first is a pilot study which aimed to define the most reliable algorithm and the set of parameters useful to assess the performed postural shifts or *In chair Movements* (ICM), which result useful to characterize postural strategies in the long term-monitoring. In this regard, a pilot study was conducted in which two different algorithms for the ICM computing were tested, based on different parameters and having different thresholds. The chosen algorithm was used, together with trunk sway parameters, to evaluate postural strategies in the other three experiments of this thesis.

The second and the third studies evaluated sitting postural strategies among bus drivers during regular, long-term work shifts performed on urban and extra-urban routes. The results, in this case, showed that, all drivers reported a constant increase in perceived discomfort levels and a correspondent increase in trunk sway and overall number of ICM performed. This may indicate the adoption of specific strategies in order to cope with discomfort onset, a fatigue-induced alteration of postural features, or both simultaneously. However, it was interesting to observe differences in ICM vs trunk sway trend considering the single point-to-point route in the case of urban drivers. This difference between may indicate that these parameters refer to different aspects of sitting postural strategies: ICM may be more related to discomfort while sway may be more representative of task-induced fatigue. Trunk sway monitoring, as well as the count of ICM performed by bus drivers may thus be a useful tool in detecting postural behaviors potentially associated with deteriorating performance and onset of discomfort.

Finally, the last experiment aimed to characterize modifications in sitting behavior, in terms of trunk sway and ICM among office workers during actual shifts. Surprisingly, results showed a decreasing trend in trunk sway parameters and ICM performed over time, with significant

modifications in sitting posture in terms of trunk flexion-extension. Subjects were also stratified basing on their working behavior (staying seated or making short breaks during the trial) and significant differences were identified among these two groups in terms of postural sway and perceived discomfort. This may indicate that the adoption of specific working strategies can significantly influence sitting behavior and discomfort onset.

In conclusion, the trunk sway monitoring along with the ICM assessment in actual working environments may represent a useful tool to detect specific postural behaviors potentially associated with deteriorating performance and onset of discomfort, both among professional drivers and office workers. Moreover, they might effectively support the evaluation of specific working strategies, as well as the set-up of macroergonomics interventions aimed to improve working conditions (in terms of workplace ergonomics and shifts schedule), which may have an impact on workers' wellbeing and productivity.

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List of Abbreviations

AP	Antero Posterior
BOS	Base of Stability
CA	Contact Area
COG	Center of Gravity
COM	Center of Mass
COP	Center of Pressure
CVD	Cardiovascular Disorders
EC	Ellipse’s Centroid
EMG	Electromyography
FFT	Fast Fourier Transform
ICM	In Chair Movements
IMU	Inertial Measurement Unit
LBP	Low Back Pain
LOD	Limit of Detection
ML	Medio-Lateral
MP	Mean Pressure
MSDs	Musculoskeletal Disorders
MVC	Maximum Voluntary Contraction
NHANES	National Health and Nutrition Examination Survey
NHTS	National Household Travel Survey
PP	Peak Pressure
REBA	Rapid Entire Body Assessment
RULA	Rapid Upper Limb Assessment
SA	Sway Area
SDT	Settling Down Time
sEMG	Surface Electromyography

SP	Sway Path
VDU	Visual Display Unit

Chapter 1

Sitting posture in modern society

In this chapter the background information on the role of sitting posture in modern society will be discussed in order to better understand the purposes of this study. In fact, sitting posture represents the most widespread posture adopted worldwide due to changes in work tasks, mainly driven by the technology boom of last decades. This phenomenon has been also accompanied by a parallel growing interest of researchers and practitioners due to the strong implications in terms of design and ergonomics features. The chapter also include the detailed description of the aims and of the roadmap of the present study.

1.1 Context

Although sitting is one of the natural postures of human beings, its adoption in the context of sedentary behaviors has progressively and dramatically increased over last decades. Compared to our parents (and even more to our grandparents) we are spending increasing amounts of time in environments that limit our physical activity and require prolonged sitting (Owen, Sparling, Healy, Dunstan, & Matthews, 2010a) at work, at home, and while commuting (using transportation systems such as cars, trains, buses etc., Hill et al., 2003) to move for work and leisure time purposes.

A National Health and Nutrition Examination Survey (NHANES) 2003–2006 study which measured the amount of sedentary time in US adults, found that Americans aged 20-69 sat between 8 and 9 h per day (Healy et al., 2011). Recent evidences also shown that, especially at work, people spend about 2/3 of their working time sedentary (Ryan, Grant, Dall, & Granat, 2011; Thorp et al., 2012). As a result, sitting time at work has reached the average of 6.3 h/day (Chau, Ploeg, Merom, Chey, & Bauman, 2012). Other significant contributors to daily sitting time, like watching television and driving personal vehicles, are at all-time highs, with estimates of nearly 7 hours (Healy et al., 2008) and 1 hour, respectively (Nielsen Company, NHTS 2010). Other studies found that, on average, people spend only 4% of waking hours in moderate-vigorous intensity activities, while the rest of the time is dedicated to either sedentary or light intensity activities (Healy et al., 2007). The progressive growth in occupational sitting time over the past 40 years has been well documented and it is largely attributed to the shift away from agricultural jobs toward occupations associated with the technology boom (Brownson, Boehmer, & Luke, 2005; Chau et al., 2012). According to Owen et al. (2010), changes in transportation, communications, workplaces and domestic-entertainment technologies have played an important role in modifying human behavior.

Modern jobs, along with the development of technology, led to an overall increase in time spent sitting: sitting has, in fact, become the most common posture both during work (Li & Haslegrave, 1999) and leisure (Bibbo, Carli, Conforto, & Battisti, 2019), with a currently increasing trend (Jans, Proper, and Hildebrandt 2007; Saidj et al. 2015; Hadgraft et al. 2015; Bontrup et al. 2019). According to the U.S. Bureau of Labor statistics the all-jobs rate of sitting was around 39% in 2016 (www.bls.gov). However, the mix of standing versus sitting time at work, depends on the kind of occupation. For example, waiters and waitresses spend more than 96 % of their workday standing or walking and just 4% sitting while, in contrast, software developers spend an average of 90% of their workday sitting. Other occupations in which workers sit most of their shifts include bus drivers (including public transport, public school or special client transportation) who spend an average of 82.4% of their workday sitting, accountants and office workers (80.7%), and insurance sales agents (80.3%) (www.bls.gov/ors).

Similarly to what occurred for working time, leisure time has also become more sedentary, starting with the advent of the television (Agarwal, Steinmaus, & Harris-Adamson, 2018). In fact, since 1950 there has been, a linear increase in the number hours spent watching television (Fig. 1.1, Healy et al., 2008). This phenomenon was also accompanied by an increase in number of individuals who choose to watch sports instead of actively participating in them (Agarwal et al., 2018; Brownson et al., 2005).

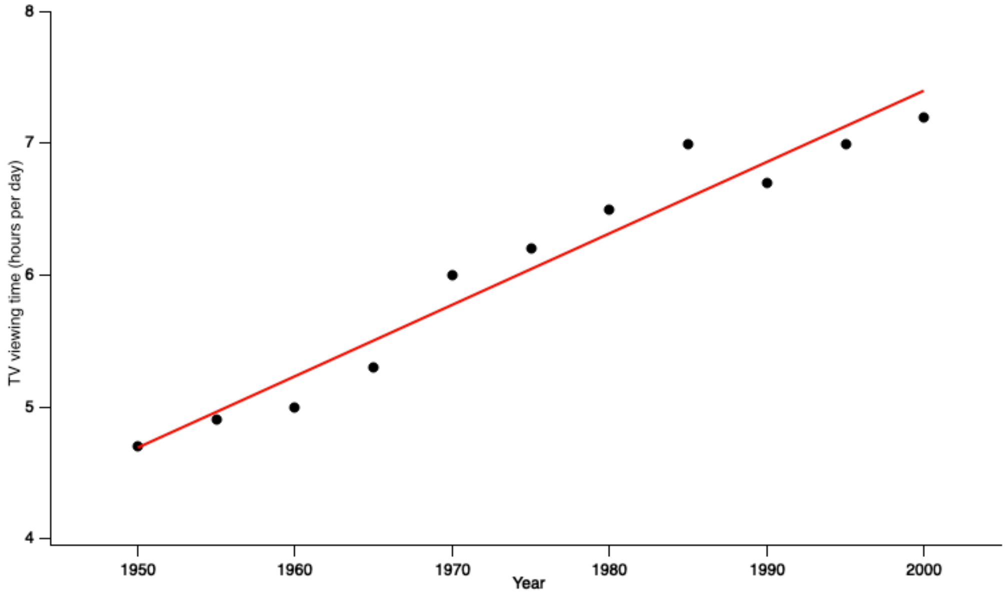

Figure 1.1: Increase in hour spent in TV viewing between 1950 and 2000. Data from Healy et al. (2008).

For these reasons, due to their spread and growth worldwide, *sedentary behaviors* in general (TV viewing, computer use, workplace sitting, and time spent in vehicles), have thus emerged as a new focus for research on physical activity and health ((Hamilton et al. 2008; Levine, Schleusner, and Jensen 2000; Owen, Phillip B. Sparling, et al. 2010; Pate, O'Neill, and Lobelo 2008). Findings in this field have thus proliferated and recent studies confirmed the hypothesis that metabolic, chronic diseases and the risk associated for musculoskeletal disorders, correlate with prolonged sitting (Xu, Li, Huang, Amini, & Sarrafzadeh, 2011). Moreover, an association between prolonged sedentary periods and all-cause morbidity and mortality has been reported (Carter, Hartman, Holder, Thijssen, & Hopkins, 2017; Owen et al., 2010b; Perlmutter, Lin, & Makhsous, 2010).

However, many scientific questions still remain to be answered before it can be concluded that these adverse health consequences are uniquely due to excessive sitting or poor sitting behaviors. In particular, the causes leading to a higher risk of musculoskeletal disorders, such as low back pain (LBP), are not clearly related with sitting behavior, and this has been a primary focus for many researchers in the ergonomic field (Andreoni et al. 2002; Fenety, Putnam, and Walker 2000; Kyung and Nussbaum, 2008).

To date, many studies attempted to objectively investigate sitting posture features and their connections with potential health risks. In particular, several of them (both in the lab and field studies) reported high rates of low back pain in workers whose occupations involve extended periods of static sitting (Gallagher & Callaghan, 2015; Karakolis, Barrett, & Callaghan, 2016). Interestingly, perceived discomfort seems to be an early predictor for future musculoskeletal disorders (Sauter, Swanson, Waters, Hales, & Dunkin-Chadwick, 2004) and its objective evaluation has been widely investigated in recent times. Nevertheless, although several approaches are available to this purpose, they appear quite variable in terms of complexity, accuracy and cost and poorly standardized.

1.2 Aims of the Study

Given the lack of standardized methods for evaluating discomfort under actual working conditions, this study focuses on providing an experimental approach, based on the analysis of seat-body contact pressures-derived information, to quantitatively assess the postural strategies among two categories of sedentary workers, such as bus drivers and office workers.

The primary purpose of the research is to detect and characterize possible postural strategies adopted by workers forced to maintain prolonged sitting postures, and possibly define their relationship with discomfort and/or fatigue, during actual long-term shifts. In particular, the idea is to verify the feasibility of use of parameters derived from trunk movements over the seat and sudden body shifts as a possible way to remotely monitor (through sensorized workstations) the workers' physical state as the shift progresses. This could possibly lead to work schedule and workplaces modifications in order to prevent or alleviate discomfort and fatigue onset.

1.3 Thesis overview

In the first three chapters context and background for the study are provided, along with an overview on sitting posture biomechanical features and on risks related to prolonged sitting. The fourth, fifth and sixth chapters describe the materials and the methods while last chapters focus on the particular experiments and their relative results. In particular:

Chapter 2 provides information on biomechanics of the sitting posture with particular focus on the loads acting on the spine. An overview on principal risks related to prolonged sitting will be given and their relationship with discomfort and fatigue will be introduced.

Chapter 3 provides a discussion on the concepts of comfort and discomfort and the methods generally employed for their evaluation (i.e. by subjective and objective measurements). A brief explanation of the most used objective methods will be conducted.

Chapter 4 analyzes in detail the body—seat contact characterization methods commonly used for the evaluation of seating (dis)comfort. In particular, the principal algorithms used in literature will be described, along with an explanation and an evaluation of their effectiveness and reliability.

Chapter 5 describes the principal contact pressure technologies with particular reference to thin flexible sensors, used for body-seat contact evaluation in the ergonomics research and design fields. Detailed description of the hardware for the particular sensor used in the present work will be then given.

Chapter 6 describes the general experimental set-up employed in each of the particular studies of this thesis, such as the population, data collection, data processing and statistical analysis.

Chapter 7 describes the pilot study conducted in order to choose the best algorithm to identify postural shifts on a chair over time. These, referred to as "*In Chair Movements (ICM)*", are in fact here measured using an innovative algorithm chosen by means of an iterative method based on pilot tests data.

Chapter 8 examines postural strategies of professional bus drivers during actual long-term driving sessions in urban area, through the analysis of ICM trend and trunk sway with shift time. Some of the results presented in this chapter have been published in conference proceedings.

Chapter 9 gives a characterization of modifications in trunk sway and ICM in experienced bus drivers during actual shifts performed on extra-urban routes. The results presented in this chapter have been submitted to a scientific journal and are currently under review.

Chapter 10 evaluates movement patterns in a cohort of office workers, performing computer tasks while continuously seated, by means of ICM and trunk sway analysis. The results presented in this chapter have been submitted to a scientific journal and are currently under review.

Chapter 11 concludes the thesis by outlining the main findings of the study, illustrates limitations and challenges faced, and discusses future directions.

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Chapter 2

Sitting posture Biomechanics

The aim of this chapter is to provide information on the main features of sitting posture from the biomechanical point of view, by describing the characteristics of loads acting on the musculoskeletal system. Based on such information, an overview of the risks related with prolonged sitting will be provided, along with their connection with perceived discomfort, which is often considered an early predictor for poor sitting.

2.1 Sitting posture

The ability to reach and maintain an autonomous sitting position is achieved between the sixth and eighth month of life, as an automatic mechanism aimed to support more advanced functions such as visual exploration, hand-eye coordination and other important tasks, which would otherwise be impossible to perform or less effective. In the subsequent years, the mechanism of conscious and voluntary sitting becomes more and more efficient, stable and safe. Sitting posture facilitates performances of specific activities and it is then used in a wide range of contexts and progressively improved with growth.

Under physiological conditions (i.e. absence of neurological and/or orthopedic impairments) sitting posture shows similar kinematic and kinetic characteristics in all individuals, with differences related to physical conformation, particular type of posture adopted, personality, and socio-cultural factors (Occhi, 2008).

The fundamental requirements to sensorimotor control system to maintain an ideal (or at least good) sitting posture are those able to guarantee the maximum possible economy in terms of energy expenditure, comfort, safety and functionality. These objectives can be achieved thanks to the efficient interaction between internal (neuromotor system) and external (postural systems) control mechanisms.

Nevertheless, the abstract concept of *ideal posture* is somewhat difficult to fully and exhaustively address. Which is the best posture? Which posture is more indicated while sitting? And for which tasks? A unique answer to this question is difficult to find.

In fact, since any posture is harmful if maintained for a long time (Gross et al., 1994), when we think of an ideal sitting posture, we don’t refer to a single, fixed posture, but rather to a reference posture around which subjects make continuous adjustments.

The efficiency of any posture from the biomechanics viewpoint can be assessed by looking at the way skeleton and postural muscles are stressed (Gyi, 2013). Postural stress is the result of gravitational forces acting on the body (Sammonds, 2015) and forces required by muscle activity to maintain the required posture (Troup, 1978). Nachemson et al. (1986) showed that the muscular effort at trunk level required for sitting is greater than those necessary to maintain the upright posture, due to the modification of spine's physiological curvature (Fig. 2.1). In this regard, it has been reported that intradiscal pressures in the spine are 40% higher in sitting than in standing (Andersson & Ortengren, 1974).

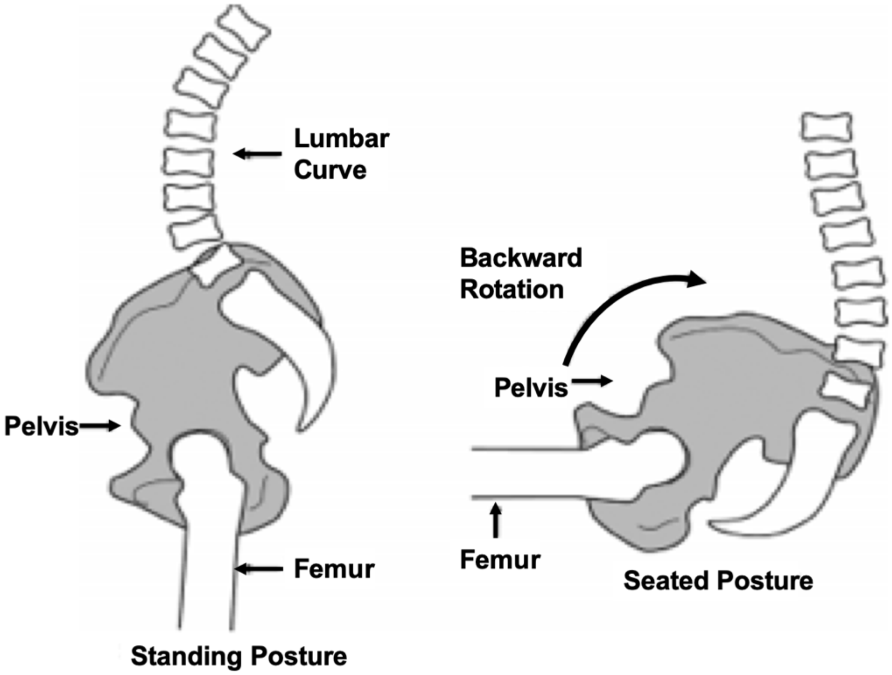

Figure 2.1 Sacrum orientation on the sagittal plane in standing vs. sitting

2.2 Biomechanics of sitting posture

To better understand the complex distribution of the forces acting on human body while sitting (especially on the spine) a brief description of sitting posture biomechanical features is given in the following paragraphs.

Pelvis

The structure of the pelvis affects (and is conditioned by) that of the upper and lower segments. The stability of this structure and its adaptability to postural changes of body segments is a fundamental prerequisite to ensure the balance of the whole system.

Sagittal plane. In a seated position, the orientation of the pelvis is significantly different with respect to the anatomical position. As an example, the inclination of the pelvis is less forward-

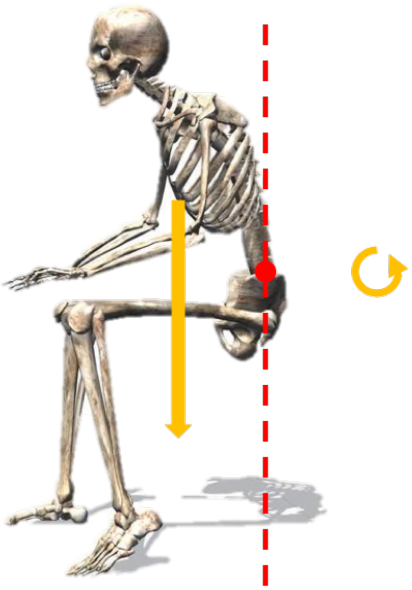

Figure 2.2: Forces and moments acting on the trunk while seated. Red line represent the vertical axis passing through the COM; the orange arrows represent the body weight force (left) and the originated moment (right)

oriented during sitting (Fig. 2.1) and also varies with the flexion angle of knees, increasing with the increase of the latter due to the progressive loosening of the hamstrings muscles (Occhi, 2008). The stability of the pelvis segment on the sagittal plane is quite precarious as the body mass supported by the hips tends to oscillate in front and behind the transverse axis of these joints, generating external destabilizing moments (Fig. 2.2). To counteract the effect of these moments, the intervention of the muscles acting on the pelvis and trunk is necessary if not supported by external elements like table, armrests, backrest, sacral support, etc.

Coronal plane. Horizontality of the pelvis is essential to ensure the right alignment of the spine and the homogeneous distribution of pressure on the areas of support; its obliquity may determine a compensatory deviation of the spine and an ischial overload (Fig 2.3).

Figure 2.3: A bad pelvis horizontality leads to ischial overload and deviation of the spine.

Lumbar Spine

Sagittal plane. The orientation of the lumbar spine in the sagittal plane is primarily conditioned by the sacral angle. Due to the reduction of the forward lean of the sacrum, lumbar lordosis during sitting is about 40% lower than in an upright position (Fig. 2.1). The values of this angle can also vary significantly according to the degree of flexion of the knees (i.e. it increases with increasing knee flexion) and the postural system adopted (shape and position of seat, backrest, footrests, possible presence of other accessory elements), and oscillates between 45 and 15 degrees (M. A. Adams & Hutton, 1983). When sitting, backwards rotation of the pelvis flattens the lumbar curve of the spine, thus significantly altering its natural shape and causing an increase in intradiscal pressures which lead to increased discomfort and poor spine health (Gyi, 2013; Porter & Gyi, 2002). While sitting with low lordosis angle (< 25 degrees), traction forces on the posterior soft tissues and compression on the anterior portions of the rachis are produced. In this configuration the nucleus pulposus of each vertebral segment is pushed backwards against the fibers of the annulus, increasing the risk of disc rupture because the posterior segments of the disc are not strong enough to withstand these loads (Michael A. Adams, Green, & Dolan, 1994). The posterior longitudinal ligaments of the spine are also considerably thinner than the anterior ligaments; moreover fibrous tissues that surrounds the intervertebral discs are not equivalent, thus forward oriented postures are much more likely to cause tearing (Lueder, 2004). On the contrary, sitting with an angle of lordosis greater than 40 degrees, increases traction loads on the anterior soft parts and compression on the posterior structures. The nucleus pulposus assumes a trapezoidal shape and is pushed forward against the annulus fibers, thus the diameter of the spinal canal (Occhi, 2008) and the nutritional intake of the disc are reduced.

Dorsal Spine

The dorsal column, due to its stiffness, is the body segment less affected by the postural structure of the segments above and below it and, for this reason, its biomechanics features won't be deeply described.

Cervical Spine

The ideal position for cervical spine would allow the optimization of the eyes orientation with no fatigue and pain. Generally, the vertical axis conducted by the center of gravity (COG) of the head passes anteriorly to the transverse axis of the occipital joint (Fig. 2.4), thus continuous activity of the extensor muscles of the head and neck is necessary to counteract the flexor moment generated by the head weight. This explains the occurrence of frequent pain which may affect the back muscles of the neck in subjects who sit for a long time and the need, at times, to tilt the backrest back (or to use other supports) in such a way to mitigate the action of gravity force.

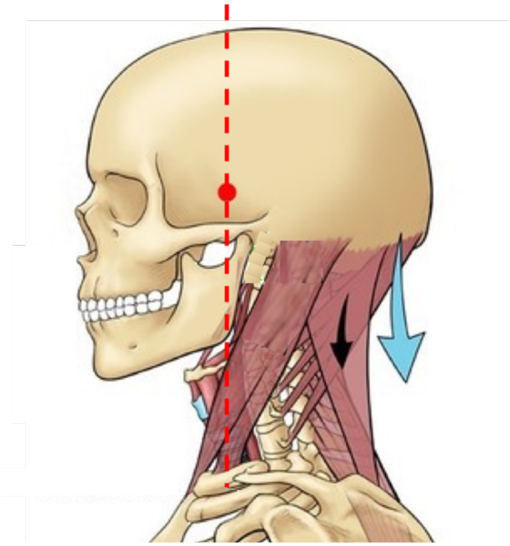

Figure 2.4: The red dot indicates the COG of the head. Passing anteriorly to the transverse axis of the occipital joint, it causes flexor moments, requiring the activation of back neck muscles.

2.3 Trunk Stability

Due to the high number of segments, the human spine system is intrinsically unstable and relies on the supporting musculature and soft tissues to achieve and maintain the stability of the trunk (Cholewicki, Panjabi, & Khachatryan, 1997). As previously mentioned, trunk muscle co-activation can provide stability of the trunk (Stokes, Gardner-Morse, Henry, & Badger, 2000), but also it requires sensory feedback from visual, vestibular, and somatosensory systems (Andreopoulou, Maaswinkel, Cofré Lizama, & van Dieën, 2015; Goodworth & Peterka, 2009; Maaswinkel, van Drunen, Veeger, & van Dieën, 2015; Wu, Duncan, Saavedra, & Goodworth, 2016) and is influenced by reflexes and intrinsic biomechanical properties of the trunk (Brown & McGill, 2009; Goodworth & Peterka, 2009; van Drunen, Koumans, van der Helm, van Dieën, & Happee, 2015). Trunk stabilization is dependent on three main systems: the passive (osteoligamentous), the active (muscular) and the neural sub-systems, which contribute to acquire, process the information and mechanically guide the action responses (Cholewicki & McGill, 1996). The automatic and reflex mechanisms of neuromotor control continuously adapt sitting positions to the performed motor task, thus ensuring optimal postural support, stability and a balanced distribution of stresses on the muscles and on the other supporting elements. The posture systems and their external supporting components (seat, backrest, footrests and accessory elements such as headrests, side rails, wedges, etc.) influence the sitting posture either directly in terms of passive adaptation to the imposed position or indirectly as active adaptation to the posture system through postural adjustment reactions. Trunk stabilization can be defined as maintaining control over trunk posture and movement, despite the disturbing effects of gravity and external-internal perturbations (E Maaswinkel, Griffioen, Perez, & Dieën, 2016).

Inadequate trunk stabilization could contribute to LBP due to high tissue strains and/or impingements (Panjabi, 1992).

2.4 Prolonged sitting and related risks

The large body of literature which investigated the negative effects originated by prolonged sitting have revealed a complex relationship among the so called “sedentary behavior” vs. physical work, energy expenditure, and other health risks (Haskell et al., 2007). In the following, the main risks associated with prolonged sitting postures will be described. When sitting for long periods of time, in addition to continuous spinal loading, compression of the blood vessels in the lower extremities (i.e. buttock and thigh region) reduces the blood flow, disrupting nutrient delivery and metabolite removal, and ultimately inducing muscle fatigue and acute discomfort (Hermann & Bubb, 2007; Gyi, 2013). The consequences of maintaining the same posture for an extended duration are multiple: as the seated posture leads to inactivity, which in turn may cause injuries and discomfort (Magnusson & Pope, 1998), poor seated postures are generally considered to contribute to high risks of cardiometabolic health concerns and musculoskeletal pain (Porter & Gyi, 2002).

Cardiovascular disorders and diabetes. Associations have been observed between sitting behavior and traditional cardiovascular risk (Stamatakis, Hamer, & Dunstan, 2011) through direct effects on the vasculature structures. Sitting time is positively associated with resting heart rate and adiposity and is negatively associated with cardiorespiratory fitness (Huynh et al., 2014). Sedentary behavior is also related to impaired vascular function and contributes to the increased risk for cardiovascular disorders (CVD) in both healthy as well as symptomatic populations

(Carter, Hartman, Holder, Thijssen, & Hopkins, 2017). Static and constrained postures interrupt blood flow in direct proportion to the muscle loads (Grandjean, 1986) and have shown to reduce muscle oxygenation even with fairly low loads (McGill, Hughson, & Parks, 2000). Bailey et al. (2019) investigated the existence of possible associations between time spent sitting and cardiovascular disease and diabetes. They reported that higher total daily sitting time is significantly associated with increased risk of CVD both with and without considering physical activity performed by subjects, even though in the latter case the risk was attenuated. Risk of Type 2 diabetes has also shown to be associated with higher overall daily sitting time when not adjusted for physical activity, but this association is not attenuated with adjustment for physical activity (Bailey et al., 2019).

Metabolic disorders. Other cardiometabolic disorders include obesity and chronic health concerns (Buckley et al., 2015; Choi et al., 2010; Wilmot et al., 2012). Increase in arterial and venous blood pressure has been associated with sedentary behavior and contributes to vascular damage and diseases (D’Souza, Franzblau, & Werner, 2005; Tabatabaeifar et al., 2015) due to the reduced muscle recruitment demands while sitting (Antle et al., 2018). In particular, Restaino et al. (2016) explain this phenomenon stating that since flow-induced shear stress is an important physiological signal for maintaining endothelial health, it is reasonable that sustained reductions of shear stress during sitting mediate leg endothelial dysfunction. Leg swelling (or edema) is another adverse consequence from prolonged sitting caused by an increase in trans-capillary filtration, which exceeds the removal capacity of fluids by the lymphatic system (Van Deursen, Van Deursen, Snijders, & Goossens, 2000). Lack of movement is strongly associated with leg swelling (Van Deursen et al., 2000; Winkel, 1981; Jørgen Winkel & Jørgensen, 1986) as, during movement, muscles expand and contract promoting circulation. Lower leg edema is very common among sedentary people and thus increased risk of venous thrombosis (Hitosugi, Niwa, & Takatsu, 2000); it also predisposes users to venous disorders such as varicose veins (Kilbom 1986; Van Deursen et al., 2000) and increases the risk of venous thromboembolism (Healy, Levin, Perrin, Weatherall, & Beasley, 2010).

Musculoskeletal disorders. As previously mentioned, sitting for long periods leads to sustained increased intradiscal pressure (Nachemson & Elfström, 1970; Karakolis, Barrett, & Callaghan, 2016) which constitutes a negative factor for the nutrition of the intervertebral discs (Marras et al., 1995). As a result, prolonged static sitting has important implications on musculoskeletal system especially in the low back, where the L4/L5 compressive forces are higher if compared to the standing values (Agarwal, Steinmaus, & Harris-Adamson, 2018). Associated problems with prolonged sitting affecting the musculoskeletal system are also known as "Musculoskeletal Disorders" (MSDs). These include pain in the upper extremities and neck, wrist tendonitis, epicondylitis, and trapezius muscle strain. Such negative issues are highly reported among sedentary workers (i.e. office workers, drivers) and account for most of work-related occupational health problems associated with these particular jobs (Rempel et al., 2006). In this regard literature is equivocal on the related causes, as they and their severity could vary depending on different factors: for example how much time workers spend in mousing or keyboarding or work adopting awkward postures due to the workstation set up (i.e. reaching, mouse ergonomics, typing on a keyboard placed above elbow height etc., Rempel et al., 2006).

Faiks and Reinecke (1998) reported that prolonged static sitting compromises spinal structures by reducing disk nutrition, restricting capillary blood flow, and increasing muscular fatigue. In fact, after the 10th year of life, human' spine loses its ability to actively feed itself and to eliminate waste products (M. A. Adams & Hutton, 1983; Grandjean, 1986; Maroudas et al., 1975; Schoberth, 1978) and receives nourishment (and eliminates wastes) through passive changes in osmosis resulting from movement. Thus, fixed postures result in nourishment dysfunctions, with consequent spinal disorders and increased discomfort.

2.5 Relationship with perceived discomfort and fatigue

People often assume that back pain is caused by short-term (acute) events such as accidents, but evidences show that this is not always true: research suggests that long-term chronic stressors are also important. In particular, fixed postures are as likely to lead to disabling back pain as heavy manual work such as construction and acute events (Lueder, 2004). Several studies have shown that an increase in musculoskeletal discomfort can be associated with increased sitting time (Callaghan & McGill, 2001; McLean, Tingley, Scott, & Rickards, 2001; Fenety & Walker, 2002). Other authors reported that signs of body perceived discomfort while sitting may reflect an early perception of low back pain (LBP) (Søndergaard, Olesen, Søndergaard, de Zee, & Madeleine, 2010; Hamberg-van Reenen et al., 2008). Prolonged sitting is thus considered an important risk factor particularly for LBP (Pope, Goh, & Magnusson, 2002), Corlett, 2006; (Ayanniyi, Ukpai, & Adeniyi, 2010; Collins & O'Sullivan, 2015; Gupta et al., 2015): in particular, seated working periods longer than 7 h/day seem to be particularly dangerous (Cho, Hwang, & Cherng, 2012; Subramanian & Arun, 2017). In Western industrialized countries, up to 90% of people reported at least one episode of LBP within their lifetime (Airaksinen et al., 2006; Breivik, Collett, Ventafridda, Cohen, & Gallacher, 2006) which is why today LBP is referred as one of the most costly disorders among the worldwide working population (Lis, Black, Korn, & Nordin, 2007). The overall socioeconomic burden in the United States in 2006 exceeded US$100 billion (Katz, 2006). Risk of back pain is affected by our sitting habits (Bendix t al., 1996; Kelsey, 1975): for example, constrained postures can cause chronic degenerative alterations of the cervical, thoracic, and lumbosacral areas of the spine (Graf, Guggenbühl, & Krueger, 1995; Hüñting, Grandjean, & Maeda, 1980; Occhipinti et al., 1987; Polus et al., 1985) and high levels of intervertebral disk immobility (Wood & McLeish, 1974).

In addition to altered loads on the spine structures, prolonged sitting causes static durations of muscle activity (between 5-10% of the maximum voluntary contraction, MVC) that can originate muscle fatigue. This phenomenon is mainly due to a few individual motor units being recruited at the beginning of the sitting task, which stay active until the muscle is provided a period of rest (Andersson et al., 1975). These back and trunk muscles fibers, known as “Cinderella fibers” (Hägg GM, 1991; Sjøgaard & Søgaard, 1998), perform a disproportionate amount of the work, with sustained submaximal contractions maintained for long periods which may induce a high level of discomfort and neuromuscular fatigue (Hosea et al., 1986; Jørgensen et al., 1988; Baucher & Leborgne, 2006; El Falou et al., 2003).

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Chapter 3

Sitting comfort/discomfort and its measurement

Research on seat comfort, often practiced by ergonomists, is today well recognized as an applied science. Interest on this field is motivated by the arising concerns for health and well-being of consumers and the fact that comfort is an essential aspect for final customers and consumers (Mike Kolich, 2008). Since the way seat and people interact highly impacts on comfort/discomfort sensation, the understanding of the mechanisms underlying this relationship is of essential importance. However, to date a limited number of researches investigates the interaction between a sitter and a seat and even less studies focus their attention to investigations of discomfort during prolonged tasks. Moreover, there is a lack of standardized protocols to investigate such phenomenon, and literature reports findings somewhat contradictory. Research continues to develop tools for understanding the interaction between the sitter and seats, and in recent years a particular interest on long duration sitting, especially during work, can be observed. Advances in ergonomics research may play an important role in ensuring better design for seats, workstations and work schedules in the future.

3.1 Defining Comfort and Discomfort

Although the word “comfort” expresses a well-established theoretical concept, it remains quite challenging to provide a precise definition for it, as comfort can be either a physical sensation, a psychological state or both simultaneously (Pearson, 2009). To date there is not a universal accepted definition of sitting comfort or discomfort (Helander & Zhang, 1997; Lueder, 1983), and it has been beyond dispute that they are feelings or emotions subjective in nature (De Looze, Kuijt-Evers, & Van Dieën, 2003). Generally speaking, comfort can be commonly referred to as “a pleasant feeling of being relaxed and free from pain” (Cambridge Dictionary, nd) and the absence of pain is an essential feature influencing seat ergonomics. This definition only takes into account positive emotions and feelings, while comfort should be instead treated as an entity influenced by a variety of different factors.

Understanding nature and influence of such factors is generally highly important for manufacturers (M Kolich, Seal, & Taboun, 2004) as it is an essential aspect for final customers and consumers (Mike Kolich, 2008). Authors have supposed that comfort is a separate construct from discomfort as comfort relates more to ‘aesthetics’ and ‘natural feelings’ (Shackel, Chidsey, & Shipley, 1969) and it can be associated with feelings of relaxation, well-being, satisfaction, aesthetics and luxury. For example, previous authors observed that a good aesthetics of a chair may result in an initial perception of it as comfortable (Kleeman, 1981) or that two identical chairs would result in different perception of comfort, depending on aesthetics of the material used to cover them (Zhang et al., 1996). These results confirm the perception of comfort as a sensation, but the only evaluation of seat ergonomics on initial comfort perception cannot not take into account many factors that negatively impact on comfort ratings in the long term: humans have no comfort receptor but a battery of pain receptors (nociceptors, Mansfield, 2005).

On the basis of the above-mentioned considerations, it seems important to distinguish between comfort and discomfort. Sitting comfort can be generally associated with positive emotions and feelings, while discomfort is more often associated with biomechanical and fatigue factors (Zhang, Helander, & Drury, 1996a). In this regard, even though some authors suggested that both terms are part of the same entity, as opposing ends of a continuous scale, Helander & Zhang (1997) state that sitting comfort and discomfort are orthogonal and not simply the opposite of each other: as shown in Fig. 3.1 absence of discomfort does not automatically result in comfort. Comfort will be felt when more is experienced than expected. The model proposed by Helander & Zhang (1997) highlights that discomfort is related to physical characteristics of the

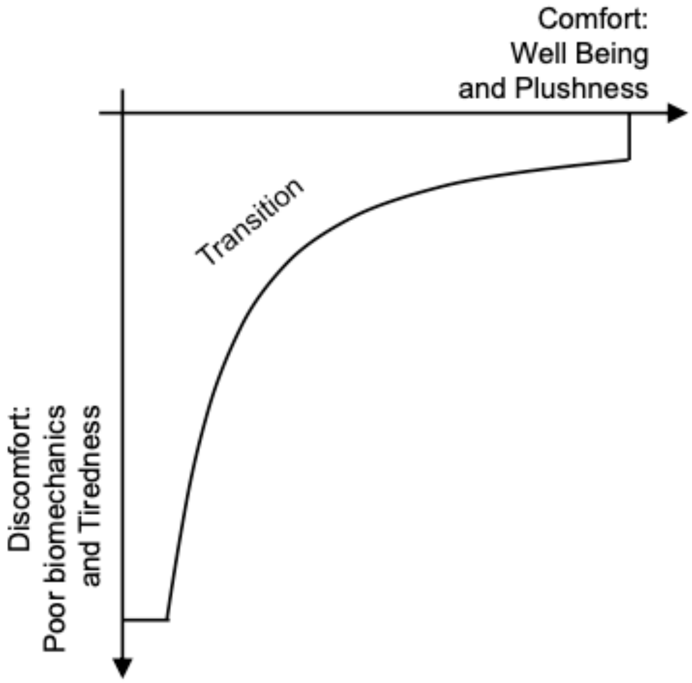

Figure 3.1: Hypothetical model of comfort and discomfort (Helander & Zhang, 1997)

environment, like posture, stiffness and fatigue, while comfort is related to luxury, relaxation or being refreshed (Vink & Hallbeck, 2012). Then, when we refer to sitting ergonomics, the practical definition of *comfort* and *discomfort* still remains challenging.

Basing on the Helander & Zhang (1997) model, comfort and discomfort have been, over the last decades, treated as two completely different entities, having different sets of characterizing factors. One of the most exhaustive models, proposed by De Looze et al. (2003), highlights the

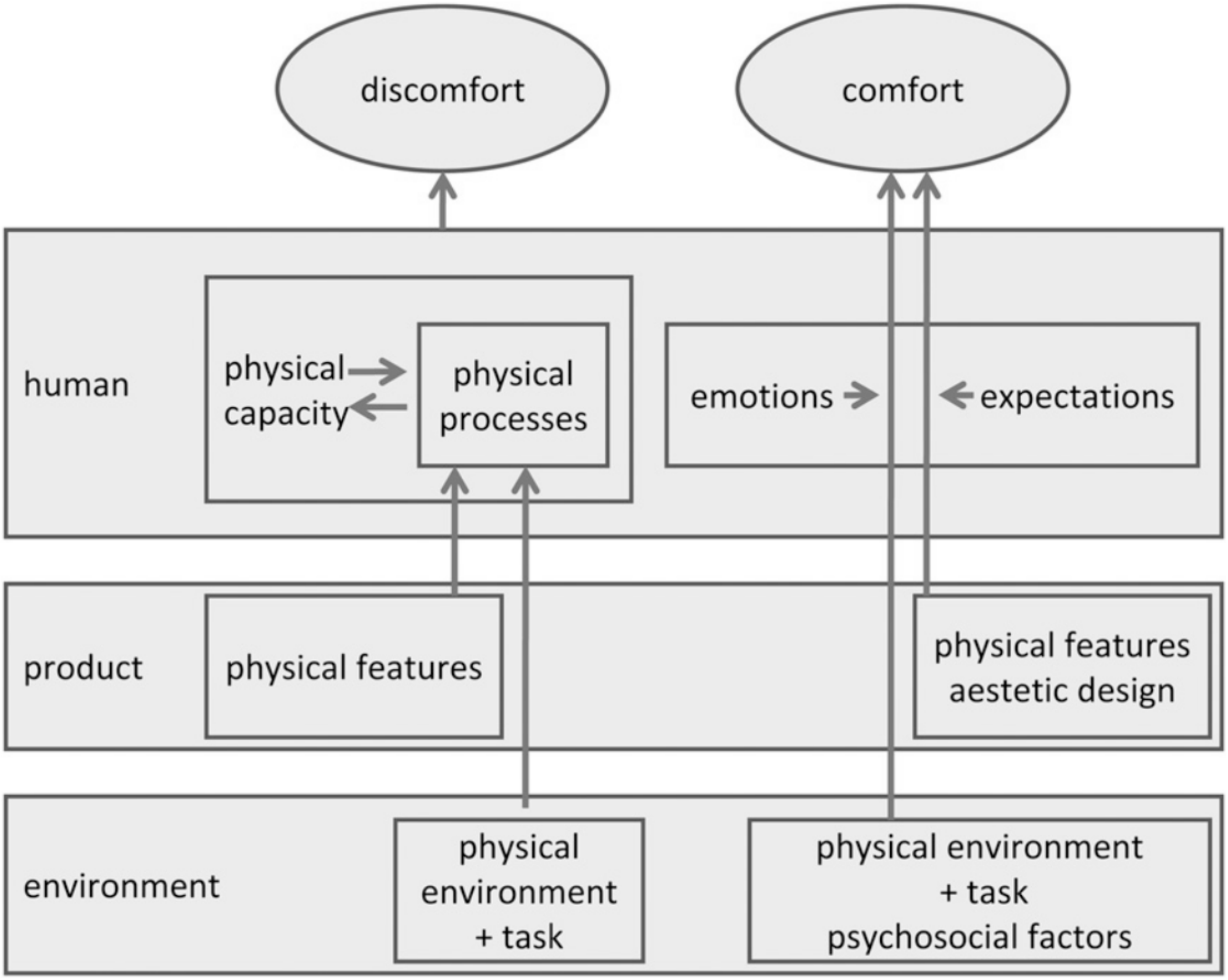

Figure 3.2: Theoretical model of comfort and discomfort and its underlying factors at the human, seat and context level (De Looze et al., 2003)

main factors affecting comfort and discomfort, describes the main differences between the two entities, how they interact and influence each other (Fig. 3.2).In this theoretical model, the left side concerns discomfort, while the right side concerns comfort only. At the human level, the physical parameters involved in the etiology of discomfort (Armstrong et al., 1993; Winkel & Westgaard, 1992) include exposure, internal dose and response capacity. According to Armstrong et al. (1993), exposure is represented by the external factors producing a disturbance of the internal state of an individual (Vink & Hallbeck, 2012). The impact that the external exposure has on internal response depends on the physical capacity of the individual. When referring to a seated posture, the external factors that can have an impact on the subject are the physical characteristics of the seat (shape and stiffness), the environment (table height, workplace configuration) and the task performed. Their influence on subjects can vary in terms of muscle activation, intradiscal pressure, nerve and circulation inclusion, skin and body temperature causing chemical, physiological, and biomechanical responses. The factors influencing comfort are also divided in human, seat, and context levels. At the context level, both the physical and psychosocial factors (such as job satisfaction and social support) have an important role in determining the overall comfort level. At the seat level, the aesthetic design of a seat as well as the seat’s physical features may affect the feelings of comfort, while at the human level, the influential factors are assumed to be individual expectations and other individual feelings or emotions (Vink & Hallbeck, 2012).

Basing on this model, Vink & Hallbeck (2012) recently proposed a new concept of the comfort-discomfort paradigm, reported in Fig. 3.3, where comfort and discomfort are still separate entities, but can be influenced by the same factors. In this model, the interaction (I) with an environment is caused by a contact (physical or non-physical) between the human, the product and its usage. Contact has effects (H) in internal human body (i.e. tactile sensations, body posture change and muscle activation).

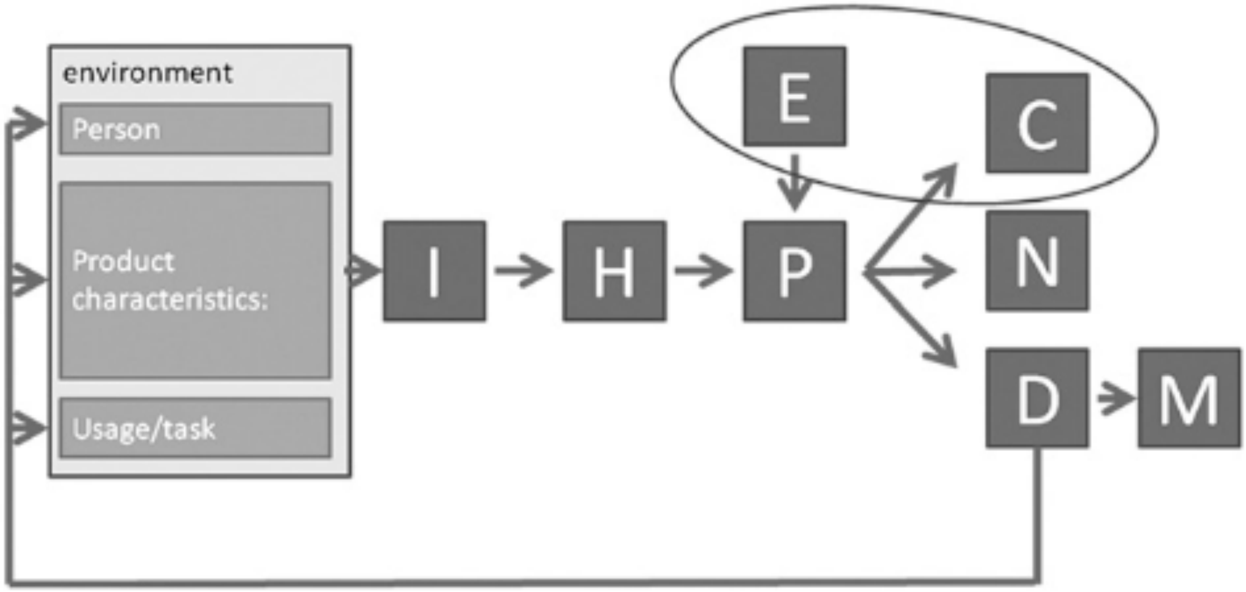

Figure 3.3: The proposed comfort model based on 10 papers review by Vink & Hallbeck

The perceived effects (P) are influenced by both the human body effects and expectations (E). These can be interpreted as comfortable (C) neutral (N) or uncomfortable, thus leading to discomfort (D). With this kind of model, it could happen that both comfort and discomfort are experienced at the same time (seat could be perceived as uncomfortable but the environment may be perceived as comfortable). The discomfort could also induce musculoskeletal complaints (M). The feedback loop to the person is activated when the discomfort sensation is too high, and an action is needed (i.e. shifting in the seat, adapt the product or to change the task) in order to alleviate the unpleasant sensation. Finally, the circle putting together E and C means that expectations are linked to comfort sensation: too many expectations are most likely induce to experience discomfort.

As seen, discomfort, described as an *unpleasant state of the human body in reaction to its physical environment* (Helander & Zhang, 1997), is thought to be a more specific and identifiable entity than comfort, as it involves the muscular and skeletal systems and is also associated with pain, tiredness, soreness, numbness, and fatigue factors (Sammonds, 2015). Many authors report, in fact, that discomfort is a consequence of physical loading associated with negative feelings of pain, pressure, hardness and irritation when referring to sitting (Peter Vink, 2004), suggesting that discomfort is concerned with physical factors and stresses acting on human body. Moreover, subjective levels of discomfort are also known to be related to poor biomechanics, circulation and increased levels of fatigue (Zhang, Helander, & Drury, 1996b). For these reasons, discomfort has been widely investigated in research and is generally addressed as an early detector of musculoskeletal disorders. Thus, discomfort measures have been commonly used to evaluate both ergonomic design as well as ergonomic and macro-ergonomics interventions (Sauter et al., 2004).

It seems important to highlight the possible existence of a link between discomfort and muscular fatigue (Leinonen, Kankaanpää, Vanharanta, Airaksinen, & Hänninen, 2005) as they are not isolated issues (Lohani, Payne, & Strayer, 2019). Even if, to this author’s knowledge, only few studies on their relationship have been reported, it has been hypothesized that both of them may contribute to psychological distress, disrupting cognitive performance (for example increasing the accident risk while driving). In this regard, muscle fatigue has been studied by examining changes in muscular tension in shoulder and neck muscles in drivers (Sheridan et al., 1991; Wikström, 1993; Balasubramanian and Adalarasu, 2007; Hirao, Kitazaki, & Yamazaki, 2006).

These studies show that continuous driving can cause a reduction in back muscles activity (e.g., trapezius and deltoid) and leads to an increase in fatigue.

3.2 Measuring Discomfort

Due to the potential benefits in health, economics and social aspects from reducing the adverse effects of prolonged sitting posture, many researchers focused their attention on the risk factors. In particular, attention has been paid to sedentary workers involved in activities associated with the onset of early symptoms of risk factors for health (Riihimaki, 1991), such as the level of perceived discomfort. In order to recognize/highlight the adverse effects of poor sitting behavior, in recent years the chance of a real-time monitoring of sitting posture has received particular attention (Huang, Gibson, & Yang, 2017). In particular, the quantitative analysis of discomfort in relation to prolonged sitting plays an important role in understanding the main factors that influence the transition between discomfort and pain. Understanding the relationship between sitting behavior, postural strategies and the onset of discomfort appears important in order to develop guidelines for preventing or limiting harmful effects. This might have a significant impact on optimizing both productivity and wellbeing as well as reducing risk health factors. The existing methods that have been proposed to measure sitting (dis)comfort across the field of ergonomics can be categorized into two main categories of measurement: subjective (i.e. questionnaires) and objective methods (i.e. biomechanical and/or metabolic information associated to the comfort/discomfort state).

3.2.1 Subjective Methods

Among various subjective methods that have been proposed in literature, questionnaires and scales can be considered as the most direct measures, as, like previously discussed, discomfort is mainly a subjective feeling (Richards, 1980). The use subjective ratings is currently focused solely on discomfort because it is considered more straightforward in quantifying the general wellbeing sensation (Mike Kolich, 2008).

However, the perception of discomfort is based on sensory inputs mediated by environmental variables: sensory system is a complex system and its response to pain and discomfort is highly dependent on subjects (Hermann & Bubb, 2007). Moreover, it may be difficult to be detected when, for example, attention is focused on an important task. In this case, perceptions may be attenuated, and perceived pain or discomfort could be mediated, attenuated or even absent (Sammonds., 2015). Blood chemicals may also act on the pain pathway, resulting in poor or absent awareness of either pain or discomfort (Thorfinn, Sjöberg, & Lidman, 2002) and therefore, for subjects highly engaged in tasks which involve high levels of concentration, an accurate subjective response may be difficult to quantify.

Memory recall of discomfort or pain perception may also be impaired or distorted in certain situations and only consciously perceived discomfort can be rated and clearly expressed (Zhang et al., 1996b). Even though the discomfort experienced is remembered, subjects often find it difficult to choose the right descriptors to describe their individual discomfort level at that time or experience difficulties in describing slight differences in perceived discomfort (Fenety, Putnam, & Walker, 2000). Therefore, the reliability of subjective responses has been highly questioned, especially in recent times, as new technologies allows obtaining objective data. To date, several objective measures have been implemented and proposed by researchers in order to standardize discomfort measurement. The typical approach consists in correlating objective measures obtained by means of sensors-generated information with the perceived discomfort reported subjectively. An important issue here to address is, once again, that the validity of subjective measure strongly relies on the ability of the subject to accurately describe their perceived discomfort level (Hermann & Bubb, 2007) and for this reason such tests are usually performed under controlled or ecological conditions.

3.2.2 Objective Measures of Overall Seat Discomfort

Objective measures are advantageous over subjective measures as they require less time to report, a smaller number of participants and are less exposed to measurement error or bias (Lee, Waikar, & Wu, 1988). However, good objective measures for predicting overall car seat discomfort are difficult to find in both literature and practice (Zenk, Franz, Bubb, & Vink, 2012) as there are many different of them in use across the ergonomics research field and each of these has its pros and cons.

Objective measures are indirect, meaning that they only give an estimate of an individual's sitting (dis)comfort, but they measure something else (De Looze et al., 2003) and for this reason correlations between objective and subjective measures are needed. Therefore, finding a useful method of measuring seat discomfort has been a great challenge in recent time among researchers and a high number of techniques and tools have been investigated within the field of sitting discomfort assessment, with varying levels of success. The most used methods based their algorithms on surface electromyographical data (sEMG), intramuscular pressure in paraspinal muscles of the lumbar region, spinal shrinkage, postural kinematics, pressure distribution at the occupant-seat surface, in-chair movements (ICMs), settling down time (SDT), room temperature, actigraphy and sonometry. Among these, the most used tools among researchers are the video recordings and inertial or accelerometer units to evaluate postural kinematics, electromyography to evaluate muscle activation and fatigue, and body seat contact pressure sensors, generally used to evaluate the optimal pressure distribution. The quantitative assessment of the actual posture adopted by subjects can, in fact, give important information on the perceived (dis)comfort level, as people modify their posture adopting different strategies to cope with discomfort onset.

Video recordings. Posture evaluation can be easily performed by external observers, with the support of video files. Usually, markers are applied on anatomical landmarks which are then traced in the recorded sequence. From the video it is possible to extract parameters describing the movement, such as displacement, velocity and acceleration. This technique has been widely used for early motion analyses in biomechanics field, but, along with the development of modern technologies, its use has now diminished. This method produces in fact a large amount of data when referred to long-term tasks, and video analysis requires a great effort, with the need of an operator reviewing all recordings in a subsequent phase. Observation is therefore mainly used to monitor basic postures, e.g. to determine the percentage of out-of-position postures in real-life scenarios (Dinas & Fildes, 2002; Parkin, Mackay, & Cooper, 1995).

Joint angles. Many studies have been carried out with the aim to objectively evaluate sitting postures by means of the measurement of postural angles, also obtained by photographic techniques, goniometry, optoelectronic systems, or, more recently, by inertial measurement units (IMU) (Babbs, 1979; Drury & Coury, 1982; Judic et al., 1993; Matsuoka & Hanai, 1988; Rebiffé, 1969; Andreoni, Santambrogio, Rabuffetti, & Pedotti, 2002; Anne Fenety et al., 2000; Petropoulos, Sikeridis, & Antonakopoulos, 2017; Singh et al., 2016). Joint angles evaluation allows to highlight risky postures: for example, they allow to identify alterations of spinal curvatures, which have shown to associated with higher mechanical load during static postures (Claeys, Brumagne, Deklerck, Vanderhaeghen, & Dankaerts, 2016). Non-neutral spinal postures play, in fact, an important role in the development of postural related spinal pain. Techniques for evaluation of joint ranges show a certain degree of success (Gyi et al., 1998) and, in general, they are used in conjunction with risk evaluation scales, such as Rapid Upper Limb Assessment (RULA) or Rapid Entire Body Assessment (REBA). By calculating the percentage of time spent in a specified range of angles, risk for each body part can be calculated and an overall risk score obtained with the sum of the score resulting for each body part measured (Singh et al., 2016).

Electromyography. Surface electromyography (sEMG) is a widely used tool in the study of muscle activity due to his non-invasiveness and it gives information on timing and amplitude of muscle activation (Duchene & Goubel, 1993). It is generally preferred to invasive methods of electromyography (EMG) in biomedical and ergonomics evaluations as the latter are invasive, difficult to execute, require specialized healthcare operators to be performed and are more time-consuming. By using the Fast Fourier Transform (FFT) to calculate the frequency component of the sEMG signal it is also possible to obtain information on muscular fatigue (De Luca, 1997) and to quantify an increase or decrease in muscle activation required to perform a certain task. In particular, a reduction in the mean (or median) frequency of the signal identifies the onset of muscular fatigue (Krogh-Lund & Jørgensen, 1993; Ng & Richardson, 1996; Hostens & Ramon, 2005; Balasubramanian and Adalarasu, 2007; Hirao et al., 2006; Sammonds, 2015) so they are often used in long-term evaluations.

Data obtained from a sEMG analysis provide important information on muscular activation, and it is used in sitting posture monitoring mainly on the dorsal and para-spinal muscles. However, it should be noted that is often difficult to correctly process or interpret the sEMG signals, as their low magnitude (which decreases the signal-to-noise ratio) and the fact that postural-muscles activity is often masked by other myoelectrical activity or noise (El Falou et al., 2003), makes it necessary to firstly extract the constant signal obtained from a long-term-reference recordings with no activity performed except postural control, resulting in long and complicated tests. Moreover, El Falou et al. (2003) suggest that some attention needs to be done when using myoelectrical signals as a predictor for discomfort, because the perception of discomfort does not necessarily imply the presence of muscular fatigue.

Other authors state that sEMG is helpful in identifying discomfort in fatigued and weak muscles and use it to target rehabilitation for skeletomuscular problems (Balasubramanian and Adalarasu, 2007). Recent developments on low-cost sEMG systems promote their use for many different applications. As an example, Artanto et al. (2018) used these systems to detect drowsiness by attaching it to muscles around eyelid region to capture the duration of eyelid closure.

Nevertheless, further research is needed to validate EMG's applicability in real-world configurations due to many issues related to their use.

Other objective measures. In other studies, many different measurement technologies have all been used to evaluate sitting behavior and discomfort, such as optoelectronic motion analysis (Dunk & Callaghan, 2005), force sensors (Yamada et al., 2009; Zemp et al., 2016), vibration and pressure sensors (Zemp, Taylor, & Lorenzetti, 2016).

Among all mentioned systems, pressure sensors are the most commonly used in the evaluation of sitting behavior, as they offer a relatively cheap measurement approach that is able to provide little or no influence on the subject during the measurement. Besides allowing high reliability for assessing individual sitting behavior (Kamiya, Kudo, Nonaka, & Toyama, 2008; Zemp, Taylor, et al., 2016), they are easily attachable and therefore offer a practical solution for analyzing sitting behavior of subjects on their own chair (Bontrup et al., 2019) or workstation in general. They have been also shown to be a reliable tool in predicting sitting discomfort (Andreoni et al., 2002) and for all these reasons they have been used in the present study.

As pressure sensors will be used in the present study to evaluate sitting postural strategies, in the next chapter, a brief overview on pressure sensors technology will be given along with an overview on their specific use for sitting postural strategies and comfort evaluation.

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Chapter 4

Body-seat contact pressure for sitting discomfort evaluation

The analysis of body-seat contact pressure distribution represents one of the most widely used quantitative technique to evaluate discomfort, in the literature of seat-ergonomics (Krishan, 2017), even though the interpretation of pressure data remains, to date, quite challenging. In the last decade, many efforts have been done to better understand the relationship between objective information (represented by the contact pressure data) and the subjective discomfort perception in order to develop guidelines for both manufacturers and employers. This may lead to improvements in the production processes organization, workplace design and macro-ergonomics in general, which may have a crucial impact on workers' wellbeing and productivity.

4.1 Introduction

Before discussing the role of body-seat contact pressure in the evaluation of discomfort, some considerations need to be introduced to accurately describe the exchange of forces between the human body and the seat. In particular, it is noteworthy that such interaction can be strongly influenced by the duration and the type of performed task and by the environmental conditions.

Time effect. As previously seen in case of the discomfort, the interaction between the sitter and the seat is, to some extent, dependent on time. In fact, both perceived discomfort level and fatigue are time dependent, and are able to influence the adopted posture and postural strategies, thus impacting on the contact pressure distribution. In short, time is an important factor that negatively influences the perception of (dis)comfort or fatigue. At the same time, these may originate a modification on posture and postural strategies, thus influencing the body-seat interaction. Having this in mind, it seems therefore important to evaluate the body-seat interaction as a time-dependent element, rather than as a screenshot associated to a specific posture.

Task effect. The effect of the particular task performed by the user cannot be neglected (Bendix, Winkel, & Jessen, 1985; Bishu et al., 1991; Drury & Coury, 1982). Even though during the leisure time we are free to decide when take rest periods and, in general, our posture is not constrained, many working task require to adopt and maintain prolonged sitting postures. Moreover, certain postural behaviors are forced by the particular activity performed, resulting in awkward postures. Thus, the evaluation and characterization of prolonged sitting postures and related strategies during a working shift, is crucial in order to properly design and manage tasks, workshifts, rest breaks, in such a way to enhance workers wellbeing and reduce biomechanical and metabolic risks.

Environmental factors. Another important factor influencing sitting postural strategies is the environment in which the task or work is performed. Workstation settings and ergonomics, as well as external factors are of extreme importance. For this reason, many authors decided to analyze sedentary working tasks under ecological (real or simulated) conditions (Andreoni et al., 2002; Fenety & Walker, 2002; Sammonds, Fray, & Mansfield, 2017) with the aim to faithfully reproduce the actual working conditions. However, while this approach can be easily used for some application (office working conditions can be reproduced quite well) in other cases this may be challenging. For instance, when driving, the external environment highly affects the working task: the presence of vibrations, road and traffic conditions can only be emulated in a simulator, but the result is still quite different from reality. Having this in mind, it seems important to evaluate sitting working postures in their actual settings, shifting the application from simulators to real working environments.

4.2 Interface pressure data for sitting discomfort measurement

Studies on body-seat contact pressure often emphasize the onset of discomfort considering specific locations of the interface characterized by a concentration of pressure. The validity of information on pressure distribution has been investigated by De Looze et al. (2003) in their review, where a clear association with subjective discomfort ratings was highlighted. In general, early studies found associations between the particular distribution pattern of the interface pressure and subjective discomfort ratings (Dunk & Callaghan, 2005; Kamijo, Tsujimura, Obara, & Katsumata, 1982; Kolich, Seal, & Taboun, 2004; Oudenhuijzen, Tan, & Morsch, 2003) and that the *“preferred pressure levels”* (those associated with lower discomfort levels) depend on the gender, body district and anthropometric features (Dunk & Callaghan, 2005; Kolich et al., 2004; Kyung, Nussbaum, & Babski-Reeves, 2008) such as stature: this, for example, affects neck, shoulder, buttock and thigh comfort, and may be responsible for differences in body positioning on the seat (Na, Lim, Choi, & Chung, 2005; Kyung et al., 2008; Pau, Leban, Fadda, & Fancello, 2016), thus modifying the pressure distribution on the seatpan. Drummond et al. (1982) found that, in general, 36% of the body’s weight is equally shared between ischial tuberosities and that contact pressure decreases gradually toward the distal half of the thighs. Summarizing, the results of such studies defined a sort of “*ideal pressure distribution*” across the seat based on the concept that the best seat is the one which produces the most uniform pressure distribution: with a diffuse pressure that is not directly concentrated under the ischial tuberosities, which could potentially be a source of discomfort (De Looze et al., 2003). Moreover, the need for low pressures in the distal portion of the thighs is mainly due to the fact that the underside of the thigh has a minimal resistance to deformation and thus a marked compression against the femur may lead to considerable restriction of blood flow, also inducing discomfort (Krishan, 2017).

In this regard, based upon a review of several studies, Dhingra et al. (2003) observed that softer seats provide more evenly distributed pressures, as they allow a larger effective contact area than a rigid seat. Even if this condition has generally been considered more comfortable and preferable, it should be also considered that excessively soft seats can induce postural fixity (Grandjean, 1986; Grieco, 1986) hindering the smoothness of movements. More rigid surfaces, in fact, allow higher reactivity of movements and this is of primary importance, for example, in works that require a high degree of dynamism even when seated (i.e. driving, piloting cranes, planes etc.). Postural fixity also impairs the natural blood flow and the transfer of essential nutrients through blood vessels, inducing thus to muscular fatigue (Kolich & Taboun, 2004).

Based on such considerations, for some time the occupant-seat interface pressure distribution has been considered as one of the most influential factors in seat ergonomics, especially in the automotive sector (Hertzberg, 1972; Kamijo et al., 1982; Diebschlag, Heidinger, Kurz, & Heiberger, 1988; Thakurta et al., 1995; Vergara & Page, 2002) also having an association with subjective ratings of overall seat discomfort.

But, what do we exactly mean when referring to the *pressure distribution* and what does this term means? Similarly to the concept of *force*, which includes module, direction and verse, also the pressure distribution must be suitably characterized: which features of the pressure distribution can be related, or are related to the perceived discomfort and/or the onset of fatigue? Pressure distribution is, in fact, a multifaceted entity and can be characterized in many different ways, according to its peculiar features. For instance, when we try to characterize the overall pressure distribution over time, the task may be challenging, as we need to consider a relevant number of variables (pressure on different contact regions, peak points, etc.). Fig. 4.1 shows, for example, a false-color map of body-seat pressure distribution at a certain timepoint: how can we quantitatively evaluate if this can be considered as a good pressure distribution? How can we quantitatively characterize the related posture, and which feature of this distribution we do need to consider? The answer is not obvious.

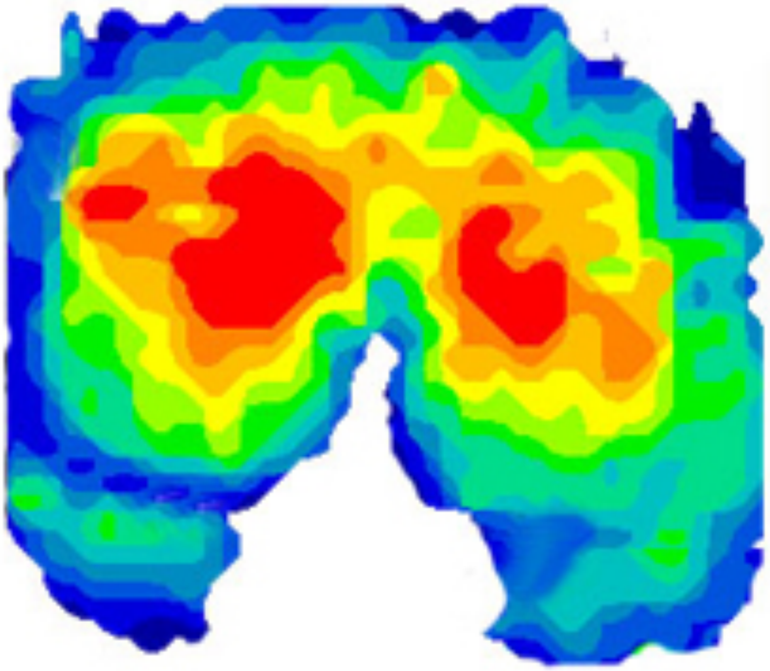

Figure 4.1: An example of pression distribution on the seatpan. Blu areas refer to low pressure values, red areas represent high pressure values.

In addition, when quantitatively analyzing sitting postures, one of the main issues which influences the pressure distribution on the seatpan is the time across which the evaluation is being performed. In several studies, the assessment has been carried out on short periods of time, ranging 2÷10 minutes. This is not sufficient, as it is known that reported discomfort may considerably vary with time (Gyi & Porter, 1999; Mansfield, Sammonds, & Nguyen, 2015); thus longer shifts are necessary for reliable and meaningful evaluations. In such studies, the continuous evaluation of contact pressure distribution over time would imply the analysis of a high number of matrices (depending on test duration and sampling frequency), thus resulting in a challenging task. For this reason, the overall pressure distribution data is mainly employed in the case of short-term evaluations, or to design the optimal chairs' shape, while, when long-term assessments need to be performed, other information such as contact area, average pressure, peak pressure, pressure gradient and pressure change (Hiemstra-van Mastrigt et al., 2017) are considered.

A number of studies have been conducted in order find/define such parameters and their relationship with discomfort; however, the explained variance in subjective perception by examining pressure features is still quite low (Hiemstra-van Mastrigt et al., 2017). Some studies, in fact, failed in detecting a clear association between pressure data and discomfort (Bendix et al., 1985; Porter, Gyi, & Tait, 2003; Carcone & Keir, 2007; Groenesteijn et al., 2012). Others were only able to find low associations (Liu & Wang, 2011) or conflicting results, reporting associations with *overall discomfort* but no association for *body parts* discomfort (Kyung & Nussbaum, 2008). Hiemstra-van Mastrigt et al. (2017) and Zemp et al. (2015) explain this phenomenon stating that studies on the correlation between pressure variables and subjective (dis)comfort are not in line with each other because of the large differences in research design. Moreover, pressure measurements can be insufficiently sensitive to indicate differences between seats, while the subjective comfort ratings are quite distinctive (Hiemstra-van Mastrigt et al., 2017). A summary of studies using pressure variables in order to assess discomfort while sitting is reported in Tab. 4.1.

These issues highlighted the need to use further information beside the sole pressure information when performing long term evaluation of discomfort; thus, the use of different types of contact pressure-derived data have been recently proposed. The main challenge here is to identify a parameter that could be representative of posture features or discomfort.

4.3 Dynamic Measurements

A common approach is to use *dynamic measurements* (Anne Fenety, Putnam, & Walker, 2000; Sammonds, 2015) as predictors of discomfort level among sitters, starting from objective pressure data, usually in form of discretized pressure points along the seat. This is, in fact, the typical output of the pressure measurements sensors for such applications, as better described in the following chapter.

Since sitting is a dynamic activity and seated subjects have been shown to move continuously (Branton and Grayson, 1967), a dynamic, time-based measure is necessary for the evaluation of sitting discomfort. The use of dynamic measurements would be, in fact, consistent with the perspective that considers sitting posture as a dynamic task (Branton, 1967, 1969; Jurgens, 1989) in which postures are continuously cycled over time (Bhatnager, Drury, & Schiro, 1985; Branton and Grayson, 1967; Fleischer et al, 1987).

In this regard, the analysis of the amount of movements performed while sitting, namely *"In Chair Movements"* (ICM), has been addressed to provide a reliable measure of sitting discomfort yet in older studies (Etienne Grandjean, Jenni, & Rhiner, 1960; Bhatnager et al., 1985; Bendix et al., 1985). Since movement while sitting is necessary to avoid undesirable static work postures (Winkel, 1986) and some movement is instead task related (Anne Fenety et al., 2000), the mathematical relationship between ICM and discomfort is not easy to understand, and thus it has been widely investigated.

Grandjean et al. (1960) were the first to propose a method that continuously recorded the body movements of a sitting subject, with the aim to evaluate the comfort feeling over time. The method consisted in analyzing the ICM trend over time, when subjects were reading, by means of a platform placed under the investigated seat, which was lying on four springs. The number of body shifts significantly increased with time. Additionally, authors reported that positive answers on subjective comfort feeling corresponded to few body movements while negative answers corresponded to frequent body movements, even if no correlation indices were reported

The first authors who documented a clear association between discomfort and ICM were Bhatnager et al. in 1985. In their experiment, twelve subjects were required to inspected printed circuit boards for 3 h with two five-minute breaks per hour. Authors measured the frequency of changes in posture by means of video recordings, while subjective discomfort was assessed basing on the Corlett & Bishop (1976) scale of body-part discomfort. results showed that both

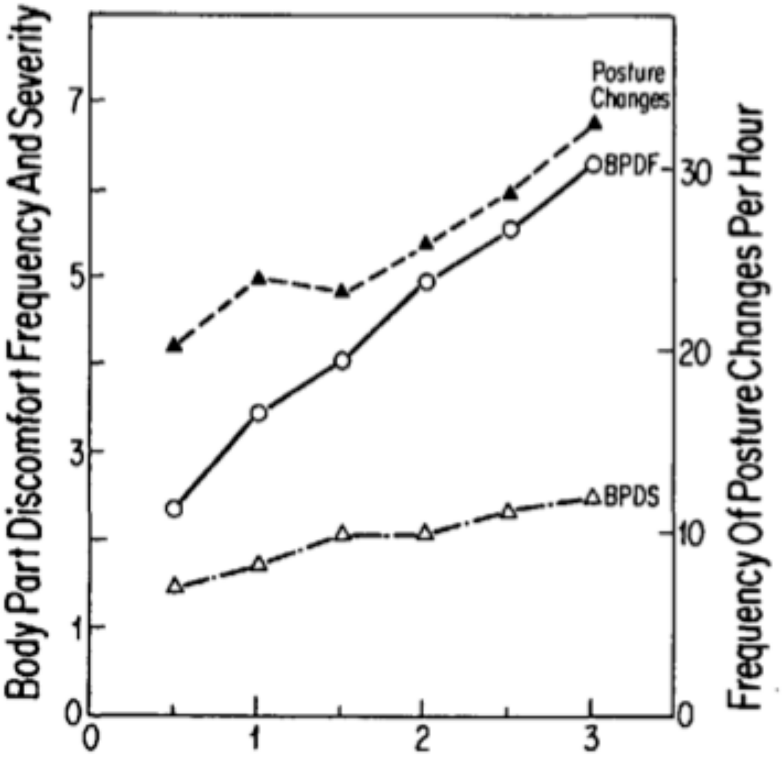

Figure ***Error! No text of specified style in document.****: Trend over time of frequency in postural shifts and perceived discomfort in Bhatnager et al. (1985) study* perceived discomfort and increased frequency of posture changes increased over time in a linear fashion, also with similar steep slopes. (Fig. 4.2)

Following these evidences, more recent authors investigated the relationship between the frequency of postural changes and discomfort in many applications, reporting, in general, the existence of a positive relationship (Fenety et al., 2000; Fenety & Walker, 2002; Liao and Drury, 2000;Na et al., 2005; Søndengaard et al., 2010; Le et al., 2014; Fasulo et al., 2019).

In particular, Fenety et al. (2000) proposed a method to continuously calculate the number of ICM by means of an interface pressure mat, applying in the field the method previously developed in laboratory settings, in order to assess its real-world reliability. During the 2 h tests, carried out in a cohort of 8 telecommunications Directory Assistance operators, the center of pressure time series (COP, the point of application of the resultant of all contact forces) were

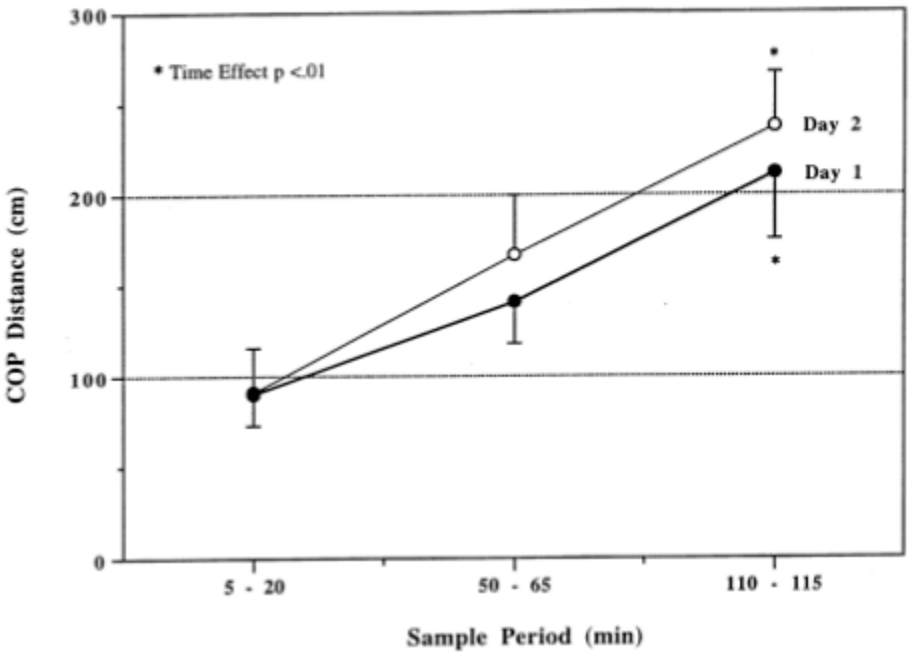

Figure 4.3:COP distance over time reported in Fenety et al. (2000) work

continuously recorded for 120 min at a 0.5 Hz frequency. ICM were operationally defined as *any movement of the chair occupant (task related or otherwise) that changed the position of the COP*. In practice, these authors considered the COP travelled distance (COP path) as a measure of ICM, summarizing data in short-time windows of 15 minutes each and discontinuously evaluating them over three test periods (5÷20, 50÷65 and 100÷115 min). Results showed that ICM significantly increased over time during the 2 h bout of sitting activity (Fig. 4.3)

Another study conducted by Na et al. (2005) examined the dynamic body pressure distribution, showing significant correlations between ICM (defined as *body pressure changes*), time and subjective discomfort ratings, when subjects were continuously driving in a simulator for 45 minutes. Body pressure changes were here identified when the mean pressure on the seatpan (or on the backrest) exceeded a certain threshold (Fig. 4.4).

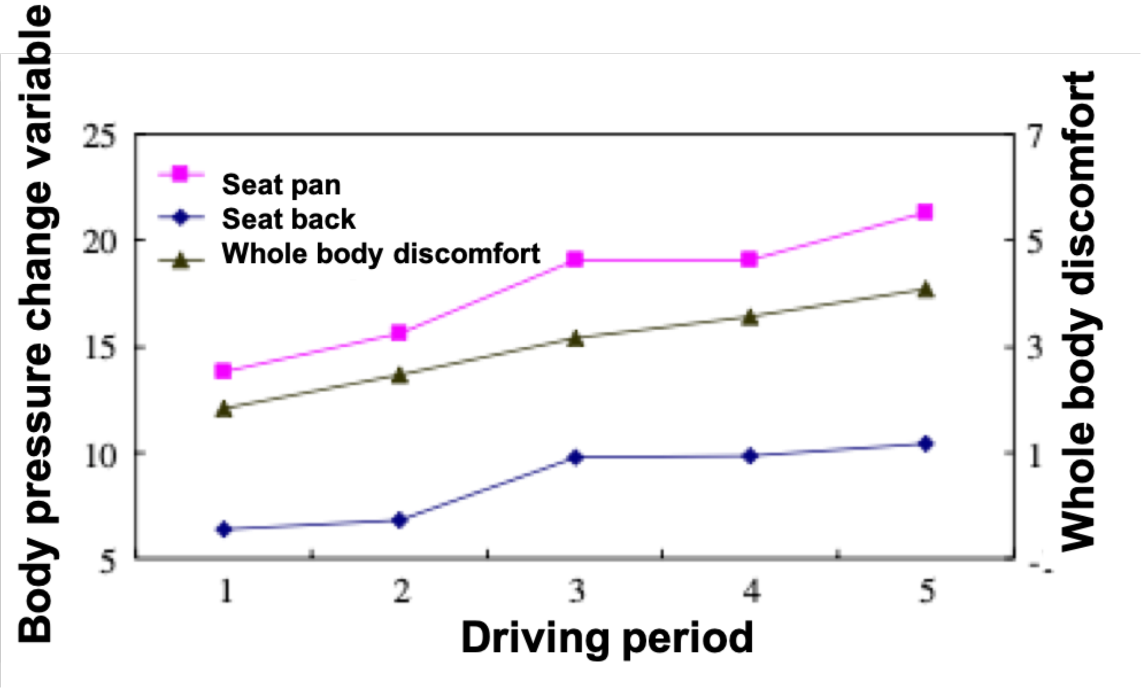

Figure 4.4: Na et al. (2005) study shows an increase in seatpan and backrest "pressure change variables" and an increase in perceived discomfort

Similarly, Le et al.(2014) used a threshold on peak pressure values in order to calculate ICM, with subjects seated in an automotive seat for 2 hours, while responding to a randomized series of prompts on a monitor by clicking a mouse. Also here, authors found an increase in number of postural shifts due to the discomfort, reporting more ICM in the later instants of the session.

Recent authors (Fasulo et al., 2019) proposed instead a method based on the shift of the COP over the seatpan, also evaluated by means of a pressure sensitive mat. In this study, contact pressure data of a cohort of university students were collected with subjects sitting while attending a class. ICM were calculated, only in the medio-lateral direction, when COP shift exceeded a predefined threshold. Results showed that ICM increase over time (Fig. 4.5), and that performing a high number of movements was due to the increase of discomfort. Authors reported that, after a movement, the decrease of discomfort was perceived, with an increase in overall comfortable state.

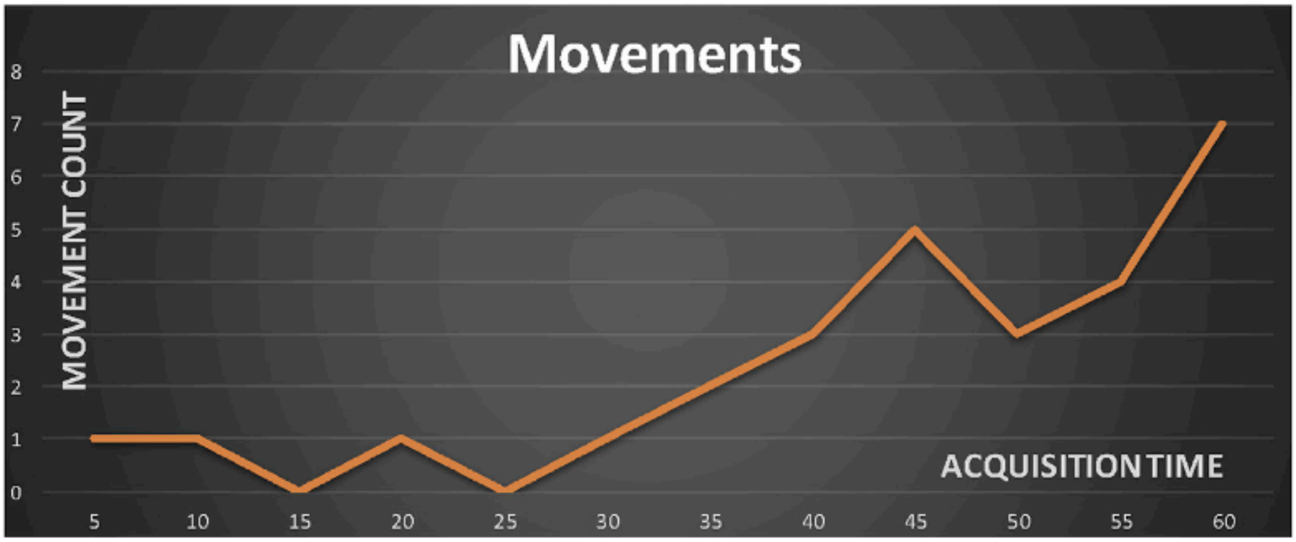

Figure 4.5: An example by Fasulo et al.(2019): increase movements over time.

Summarizing, studies generally reported that the number of postural shifts increased with time when subjects performed a number of activities, such as reading (Grandjean et al., 1960), driving a car simulator (Rieck, 1969; Na et al., 2005), piloting a boat simulator (Jurgens, 1989) or working at VDU (Fenety et al., 2000; Fenety & Walker, 2002; Michel & Helander, 1994)

These result can be justified considering the fact that postures sustained for a long period may be uncomfortable and lead to the necessity of changes over time (Vergara & Page, 2002). Any sitting posture cannot be maintained for a significant period of time without becoming uncomfortable (Graf, Guggenbühl, & Krueger, 1993, 1995), as static sitting postures cause discomfort, while movement reduces it (Aarås, Westgaard, & Stranden, 1988; Kilbom, 1987). When people first sit down, they are comfortable and move little, however, after a considerable time spent sitting, increasing discomfort generally leads to significant increases in ICM (Bendix et al., 1985; Jensen & Bendix, 1992; Fenety et al., 2000). As occupants subconsciously change their posture to minimize the effects of discomfort while sitting, discomfort may not be perceived unless it significantly compromises physical wellbeing (Helander & Zhang, 1997). People's behavior of moving unconsciously is driven by the necessity to relieve the pressure of compressed body parts with impeded blood flow (Chow & Odell, 1978; Hermann & Bubb, 2007): in this context, fidgeting may be seen as an attempt to reinstate normal blood flow which is compromised by capillary occlusion when seated in a fixed position.

Studies on the pattern of such postural changes over time hypothesize that a discomfort threshold exists, meaning that when a certain level of discomfort is reached, the individual needs to change his/her posture in order to attenuate the unpleasant sensation (Hermann & Bubb, 2007; Sammonds et al., 2017). After a movement or a change of position, a decrease of discomfort can be perceived (Fasulo, Naddeo, & Cappetti, 2019). The model that best explains

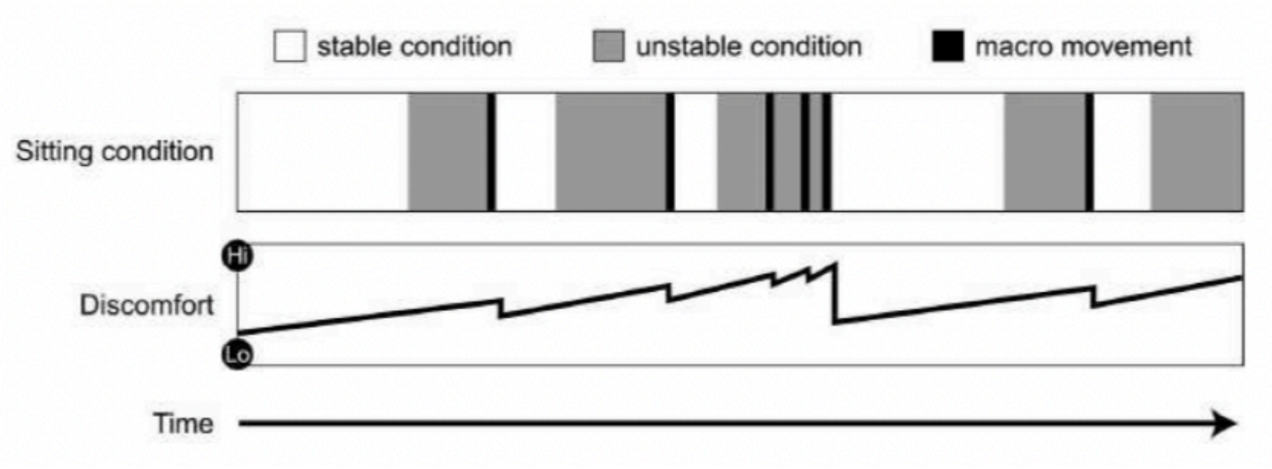

Figure 4.6: Theoretical model of sitting condition and discomfort in prolonged sitting (Fujimaki & Noro, 2005)

this phenomenon was developed by (Noro, Fujimaki, & Kishi, 2005) (Fig. 4.6). These authors investigated the pattern of changes in body pressure distribution and perceived discomfort during VDU tasks within a small sample of subjects (three males and three females). The different characteristics during 60 minutes sitting were described and compared with each other in time, highlighting that after a while the discomfort increased and, when it reached a certain level, a macro movement occurred and the pattern repeated until the end of the sitting task. In particular, in this model, the *stable condition* is represented by the maintenance of an optimal posture; when discomfort reaches a certain level, the sitting condition is shifted towards an *unstable condition*. This is followed by a more rapid increase in discomfort that causes the performing of a *macro movement,* or *postural shift*, in order to reduce the discomfort sensation. The reduction of discomfort caused by such movements becomes less effective over time, and thus the discomfort threshold is reached more quickly with respect to the beginning of the sitting bout, leading to augmented frequency of postural shifts (Sammonds et al., 2017).

This theory is thus consistent with above reported experimental results which demonstrated that during prolonged sitting both subjective discomfort and postural shifts, or ICM, increase over time in a linear trend. According to Liao & Drury (2000) shifts in posture are, in fact, distinguishable signals of discomfort: the basic assumption for studies based on ICM (or similar postural variables) is that individuals will increase the frequency and/or the magnitude of their movements as duration of sitting increases, in a manner that is influenced by their perceived level of discomfort, at a conscious or unconscious level (Fenety et al., 2000). A summary of studies investigating ICM trend over time and/or their relationship with discomfort is reported in Tab. 4.2.

4.4 Sitting postural sway

Control of posture is a function of the dynamic interaction between sensory information about the body relative to the environment and the production of appropriate motor responses for managing postural equilibrium and orientation (Horak & Macpherson, 2011), achieved by subconscious coordinated muscle activity in order to stabilize the body position or optimize postural alignment (Shumway-Cook & Woollacott, 2014). In particular, stability refers to the ability to maintain the center of mass (COM) within the base of support (BOS) throughout static or dynamic actions (Ferrari Corrêa, Ishida Corrêa, Calhes Franco, & Bigongiari, 2007). Postural control plays a primary role during functional movements and the activities of daily living such as sitting, standing, and reaching (Heyrman et al., 2014; Pavão, dos Santos, Woollacott, & Rocha, 2013).

As previously said in Chapter 2, control of the trunk is a fundamental motor skill because of its importance in nearly all voluntary activities (Goodworth et al., 2018). Trunk posture requires sensory feedback from visual, vestibular, and somatosensory systems (Andreopoulou, et al., 2015; Goodworth & Peterka, 2010; Maaswinkel et al., 2015; Wu, Duncan, Saavedra, & Goodworth, 2016) and can be influenced by reflexes and intrinsic biomechanical properties of the trunk (Brown & McGill, 2009; Goodworth & Peterka, 2009; van Drunen et al., 2015).

As said before, over time, it is expected that individuals will increase the frequency and/or the magnitude of their movements. Generally speaking, the magnitude of the movement can be quantified by considering the small oscillations resulting from the combined effort of nervous and muscular systems to keep the body balanced, referenced as *postural sway* (Pertti Era & Heikkinen, 1985). In particular, postural sway is based on excursions of the COM and the COP, and is usually calculated starting from information derived from force plates (Kim et al., 2019). Postural sway is usually investigated in the case of upright posture and it is considered a highly reliable and useful tool in characterizing the performance of the postural control system in clinical, sports and biomechanics research fields (Visser, Carpenter, van der Kooij, & Bloem, 2008). In particular, small amplitudes and low speed of sway indicate effective body control, meaning that a low effort is required to maintain a certain posture (P. Era et al., 1997). Although, as said, sway analysis is usually performed and studied in upright stance conditions, several researchers, have recently proposed a specific application of this approach to evaluate particular features of seated posture, focusing attention only on the stability of the trunk (Serra-Añó et al., 2015; Vette et al., 2010). These authors, similarly to what observed for standing, reported that trunk stability is highly influenced by sensorimotor impairments caused, for example, by neurologic conditions such as brain and spinal cord injuries (Genthon et al., 2007; Milosevic et al., 2015; Perlmutter, Lin, & Makhsous, 2010; Chen et al., 2003; Grangeon et al., 2012, 2013; Shirado et al., 2004), musculoskeletal disorders (Maaswinkel et al., 2016; Radebold et al., 2001) and neurodegenerative diseases such as Parkinson's Disease (van der Burg et al., 2006) or Multiple Sclerosis (Lanzetta et al., 2004). In general, results showed that postural sway is larger among individuals with diseases with respect to able-bodied individuals, indicating thus worse postural stability and compromised sitting balance in pathological subjects (Grangeon et al., 2012; Shirado et al., 2004).

Neuromuscular responses of the trunk have been investigated mainly by means of posturography both for standing and sitting, revealing the existence of similarities into the mechanisms of trunk control in the two different conditions (Preuss & Fung, 2008; Vette et al., 2010).

Interestingly, it has been recently reported that, during prolonged sitting posture, trunk sway tends to increase with time and this has suggested its possible use as biomarker for fatigue (Hendershot et al., 2013; Leban et al., 2017; Van Dieën, Luger, & Van Der Eb, 2012). Some authors (Fenety et al., 2000; Fenety & Walker, 2002; Søndergaard et al., 2010) also used the COP displacement, referring to it as *ICM* instead of as *trunk sway*, showing also a correlation with discomfort. In particular, it is known that tonic muscle contractions are maintained during sitting in the range of 1-3% for abdominal and 4-6% for back muscles, relative to MVC (Masani et al., 2009) and, as previously seen in Chapter 1, this can induce signs of muscle fatigue.

Given that, it could be hypothesized that, similarly to what occurs in the case of upright stance, trunk muscles fatigue is able to originate delays in neuromuscular protective reflexes and coordination (O'Sullivan et al., 2006) causing a loss in smoothness of movements (Cortes, Onate, & Morrison, 2014).

Nevertheless, only few studies have investigated this issue, along with the relationship with ICM and perceived discomfort under actual working conditions. In most cases participants were not actually required to perform any specific task whilst being monitored and providing evaluations of comfort. Such limitation may affect the validity of results as real-world conditions may significantly vary from laboratory test settings (Sammonds, 2015).

On the basis of all the above-mentioned motivations, this thesis focused its attention on the investigation of particular postural strategies among sitting workers, in real working conditions, by means of those which can be considered the most promising tools for discomfort and fatigue prediction: ICM and trunk sway parameters. These could suggest the adoption of particular strategies in order to cope with discomfort onset and/or fatigue-induced deterioration of postural control abilities.

Table 4.1: Summary of studies investigating contact pressure and perceived discomfort while sitting. Data have been selected referring to Zemp et al. (2005) and Hiemstra van-Mastright (2017) reviews.

Authors (year)	**Pressure parameter**	**Discomfort**	**Results-Conclusions**
Bendix et al. (1985)	Seat pan and backrest pressure: pattern change of pressure distribution using self-organizing map to define three different sitting conditions (macro movement, unstable and stable conditions)	Five-point scale questionnaire	Discomfort and sitting conditions follow a typical pattern: Discomfort increases after a while until it reaches a certain level where a macro movement occurs. This pattern is repeated with increasingly shorter cycle times until continuous macro movements occur. The whole pattern cycle is also repeated over time.
Brienza et al. (2001)	Mean pressure of the seat pan and the backrest	Numerical rating scale with six verbal rating terms (bad, poor, average, good, very good, excellent)	Lower mean pressures on the seat pan and the backrest are associated with higher comfort ratings.
Carcone and Keir (2007)	Mean peak backrest pressure Backrest contact area seat pan contact area	Comfort ranking of backrests	Only qualitative associations were de- scribed of some pressure variables and ranking of backrests
Chen et al. (2007)	Qualitative description of pressure distribution based on 3D pressure distribution images compared to the body pressure distribution rule	Subjective evaluation of 3 items: but- tock comfort, thigh comfort, overall comfort on a 10–point scale (ranging from very uncomfortable to very comfortable)	No correlations were calculated
De Looze et al. (2003)	Objective measures of comfort and discomfort, including pressure distribution	Subjective measures of comfort and discomfort	Seven studies were found: three of them reported correlations (Yun et al. 1992; Thakurta et al. 1995; Vergara and Page 2000) between pressure variables and comfort or discomfort; two others (Kamijo et al. 1982, Tewari and Prasad 2000) reported associations
Goossens (1998)	Pressure on the left buttock (circle with a diameter of 30 mm)	Visual Analogue Scale (VAS) with the two endpoints: “no pain” and “extreme pain”	Subjects are able to translate applied pressure on the buttocks into perceived discomfort
Goossens et al. (2005)	Pressure on the ischial tuberosity (circle with a diameter (d) of 10 and 20 mm)	Sensitivity of pressure differences on the ischial tuberosity	Subjects are able to perceive pressure differences of around 10e15%
Groenesteijn et al. (2009)	Peak pressure, distribution pattern	Six-point questionnaire with 8 questions about comfort aspects of seat, backrest and total chair comfort ranging from “very bad” to “very good” (after 5min use) Six-point questionnaire with 4 questions to compare seat A and B regarding comfort aspects of seat, backrest and total chair comfort ranging from “much worse” to “much better”	Peak pressure data of the short-term study are in line with the short-term comfort and long-term comfort as well as discomfort, as all measures showed no difference between the two chairs.

Gyi and Porter (1999)	Average seat ratio (ratio between seat mean and back mean) Maximum pressure for different areas. Mean pressure for different areas Standard deviation of the mean pressure for different areas Pressure area for different areas	Body part discomfort on 7–point scale ranging from very comfortable to very uncomfortable for the right but- tock, right thigh and the lower back	Significant correlations were found between mean lower back pressure and lower back discomfort, and between buttock discomfort and iT area pressure variables, but no correlation coefficients were reported
Kyung and nussbaum (2008)	Average contact areas, contact pressures and peak pressures of different regions (upper/lower back, left/right buttock, left/ right thigh) and ratios of a specific region divided by the total contact area	Overall ratings of comfort and discom- fort on VAs scale with discomfort and comfort as extremes; separate whole body comfort and 6 local body parts (left/right thighs, left/right buttocks, upper/lower back) and discomfort rating of the 6 local body parts on a scale ranging from 0 to 10 for comfort and from 0 to -10 for discomfort.	Correlations were found between several pressure variables and ratios and overall comfort and discomfort rating and with whole body comfort rating No correlations were found between pressure variables and local body part discomfort rating Correlations were found between several pressure variables and ratios and overall comfort and discomfort rating and with whole body comfort rating. No correlations were found between pressure variables and local body part discomfort rating.
Kyung and nussbaum (2013)	Mean contact area, contact pressure, peak pressure and ratio (local measure relative to sum) for 6 body parts: left thigh, right thigh, left buttock, right buttock, lower back, and upper back	Overall rating (combination of comfort and discomfort) Whole–body comfort rating Whole–body discomfort rating	Significant correlations of weak to moderate effect were found with at least one of the subjective ratings for 22 out of 36 pressure measures (ρ ranges between -.26 and .31); the highest correlation (ρ = .31) was found between contact pressure at the right buttock and discomfort ratings
Lopez-Torres et al. (2008)	Average pressure of a user weighing approximately 70 kg (loads applied by a thigh and pelvis mannequin)	Comparison of the different mattresses' overall comfort with 4 categories: “much more”, “more”, ”less” and ”much less comfortable”	Average pressure is associated with subjective overall comfort ratings
Mergl (2006)	Percentage of load, maximum pressure, mean pressure, pressure gradient of buttocks, middle thighs, front thighs and side thighs	Discomfort measurements by body map of seat pan (regions 10–17) with a cP50 scale	Depending on the body part region and the pressure variable, the relationship between interface pressure variables and body part discomfort can be either quadratic or linear. For some body parts (middle of thigh) and some pressure variables (percentage of load, mean pressure, maximum pressure) more evidence for a relationship was found than for others
Noro et al. (2012)	Peak pressure and pressure area of the seat pan	13 questionnaires using a 5-point scale	Comfort is related to low peak pressures and high contact areas of the seat pan.

Porter et al. (2003)	Mean and maximum pressure of 6 regions: left and right ischial tuberosity, left and right thighs, upper back and lower back.	Seat feature checklist and body part comfort scale of buttocks, thighs and lower back on a 7–point scale (ranging from very comfortable to very uncomfortable)	No clear relationship was found between interface pressure data and reported comfort/discomfort
Vergara and Page (2000)	Backrest contact (“Yes” or “No”) at the level of the maximum lumbar concavity and the maximal dorsal convexity to divide the type of backrest use into four groups: backrest not used for more than 50% (A), whole backrest is used most of the time (B), mainly the support for the low back is used most of the time (C), backrest is used mainly as a support for the dorsal area (slumped posture, D)	General comfort rating based on an 11-rating scale from “extreme discomfort” to “complete relax” Body-Part Discomfort Rating (BPDQ): 12-body-part diagram with 7- point scales ranging from “extremely comfortable” to “extremely uncomfortable”	The type of backrest use is related to general comfort/ discomfort in the lumbar spine. Especially, support of the lumbar area is important to prevent local discomfort in the lumbar spine. Therefore, backrest contact evaluations can be used to objectively quantify comfort.
Zenk et al. (2012)	Percentage of the load on the buttocks and the front thighs	Short opinion about the discomfort feeling	The pressure distribution of the seat is correlated with the intervertebral pressure (lowest load on the disc for the IDEAL position). Therefore a relation between the experienced discomfort and the pressure in the spinal disc could be identified (low spinal disc pressure leads to low levels of discomfort).

Table 4.2: Summary of studies investigating ICM and discomfort while sitting.

Authors (year)	Postural shifts (ICM)	Discomfort	Results-Conclusions
Bhatnager et al. (1985)	Frequency of changes in posture by means of video recordings	Discomfort was assessed basing on the Corlett and Bishop (1976) scale of body-part discomfort	Perceived discomfort and increased frequency of posture changes increased over time in a linear fashion, also with similar steep slopes
Fasulo et al., (2019)	Threshold on COP shift	The (dis)comfort questionnaire is divided into body-parts sections.	ICM increase over time, and performing a high number of movements was due to the increase of discomfort and that, after a movement, the decrease of discomfort was perceived, with an increase in overall comfortable state
Fenety et al., 2000	COP travelled distance	No discomfort questionnaires.	ICM significantly increase over time during a 2h bout of sitting activity
Grandjean et al. (1960)	Platform placed under the investigated seat lying on four springs	Answers on subjective comfort feeling	No correlation indices were reported
Le et al.(2014)	threshold on peak pressure values	Discomfort surveys	An increase in number of postural shifts due to the discomfort
Liao and Drury (2000)	Coding scheme for postural shifts from the videotape	A body part discomfort (BPD) questionnaire. Fatigue questionnaire was also administered through the on- screen program . Borg' s (1982) category rating scale was presented in the questionnaire	A higher frequency of postural shifts was correlated with higher Borg scale
Na et al. (2005)	Body pressure change variables (number of pressure changes exceeding 15 % of the average total pressure)	Body part discomfort ratings of neck, shoulder, back, lumbar, hip and thigh on a 7-point scale	No correlations were calculated. A tenden- cy for association was found between body pressure change and body part discomfort
Søndergaard et al. (2010)	Mean centre of pressure (coP) displacement (anterior- posterior; medial-lateral) over time Standard deviation of centre of pressure (coP) displacement (anterior-posterior; medi- al-lateral) over time Sample entropy of centre of pressure (coP) displacement (anterior-posterior; medi- al-lateral) over time.	BPD index, i.e. sum of body part discomfort ratings on a 6–point scale ranging from 0 to 5 (no discomfort to worst imaginable discomfort)	Correlations were found between Centre of pressure displacement and discomfort, which indicates when discomfort increases, the sitting movement patterns became larger and more regular

4.5 References

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Chapter 5

Body-Seat contact pressure Sensing Technologies

"Ergonomics is an applied science concerned with designing and arranging things people use so that the people and things interact most efficiently and safely"
(Merriam-Webster's Collegiate Dictionary)

Ergonomics studies the relationship between people, the activities they perform, the products they use, and the environments in which they work, travel or play. The interaction between the subject and the working environment, highly influences people behavior, as well as their comfort state. The emerging interest on pressure sensing technologies in the ergonomic field is mainly driven by industry, which strongly encourages research in the field of objective (dis)comfort assessment. In recent years efforts have been dedicated to the evaluation of seats and the related postures (Gyi et al., 1998; Guenaelle,1995; Kyung & Nussbaum, 2008) as a way of meeting customers' increased need for and expectation of comfort (Andreoni, Santambrogio, Rabuffetti, & Pedotti, 2002). Ergonomics principles allow, in fact, to develop guidelines for improving and redesigning old and new products (Mokdad & Al-Ansari, 2009).

5.1 Measurement of Body seat contact pressure

Research in the field of sitting ergonomics has been conducted for over 100 years (Sammonds, 2015) but it should be recalled that chair makers started working on their optimization in terms of design and comfort since many centuries (Reed et al., 2000). Older literature on this topic is mainly focused on office and industrial sitting but, more recently, research into automotive sitting has been greatly developed (Sammonds., 2015).

Early studies were limited in analyzing the relationships between environmental factors that can affect perceived levels of worker comfort/discomfort, such as room temperature, humidity noise, lighting etc. (Galinsky, et al., 2000). As previously mentioned, the development of advanced sensing technologies has made it possible to perform measurements of the pressure distribution at the occupant-seat interface with high resolution and reliability (Reed et al., 1991). However, design constraints typical of such applications restrict the choice of sensors to those flexible and thin. In fact, such devices can be bent and have a low profile (usually thickness values of less than 5mm). This allows evaluating the contact pressures, without substantial modifications of the body-seat contact. In contrast, conventional pressure sensors cannot be used for these applications, since they are often rigid, thick, wide and expensive to be integrated in a high-density measurement system.

With these premises, to date, thin contact pressure measurement technologies have largely been employed in investigations related to comfort/discomfort assessment and developments of seat contact pressure applications for evaluation of seating postures and comfort have led to advances in human seat contact sensing technologies, especially in the industrial, clinical and research fields. The analysis of human-seat interface, with particular reference to the study of the effect of body's weight on seat comfort over time (Horváth, Antal, Domljan, & Dénes, 2017) has been recently increased, due to design and ergonomics requirements in the industrial sector, which require products to be designed according to specific functions that benefit final users (Fasulo, Naddeo, & Cappetti, 2019).

In the following paragraphs, the basic principles of pressure measurement will be described with particular focus on thin pressure sensors technology and applications.

5.2 Pressure sensors: principle of functioning

The term "pressure sensor" encompasses a large number of transducers based on different physical working principles and designed for different applications. In the present study, "pressure sensor" identifies transducers aimed to evaluate the contact pressure, i.e. the pressure existing at the interface between contacting solid bodies. Since the pressure is measured as the force acting on a given surface, pressure sensors are basically transducers which are sensitive to forces and relate such forces to a reference area, that is the area of the sensitive element of the transducer.

Pressure sensor relies on a physical reaction triggered by the application of a certain pressure, namely its conversion into a proportional electrical signal change. Most common pressure sensors are based on physical phenomena which include changes in capacitance or changes in ohmic resistance of a strain gauge or piezoelectric element, which are proportional to the magnitude of the deflection when a force is applied. A change in the resistance results in a change in the measured voltage, which can then easily be evaluated and processed by a dedicated electronic circuit. Since these transducers measure physical phenomena intrinsically continuous, the relationship between phenomena and measure should be continuous. On the other hand, the practical solutions adopted for the development of transducers, and in particular pressure sensors, is based on different solutions (continuous, discrete and binary) depending on the application. The digitalization process (necessary to computers in order to manage signals) requires the discretization by means of AD converters.

The basic principles of the most common pressure sensors will be described in the following paragraphs. Here, a preliminary description of the main features of pressure sensors for biomechanical body-seat assessment is provided.

5.2.1 Features of pressure sensors

As previously mentioned, pressure sensors act as transducers which convert the force applied on them into an electrical signal or other signal output (Hammock et al., 2013). Key parameters for the evaluation of these sensors' performances include the sensitivity, limit of detection (LOD), linearity, response time, and stability.

- **Sensitivity** is one of the most important parameters of pressure sensors as it determines the accuracy and effectiveness of the device. The pressure sensitivity can be defined as:

  $$S = dX/dP$$

  where S is the sensitivity and X and P the output signal and applied pressure, respectively.

- The **LOD** is the lowest pressure detectable with an output signal change. This pressure is also called “threshold pressure”. The LOD of pressure sensors is particularly important to the development of effective ultra-low and subtle-pressure sensors.
- **Linearity** is generally the degree to which the performance of a pressure sensor, across a specified operating range, approximates a straight line. Linearity is usually quantified as the deviation from a straight regression line and is expressed as a percentage value. In this regard, the response of pressure sensors is more accurate and reliable when working in a linear operative range.
- The **response time** is defined as the time required by a pressure sensor to produce a stable output signal after the input pressure load. Advances in instant-response display and real-time monitoring require shortening of the response time, and to date many devices with quick response capabilities (<100 ms) have been developed.
- The **operating voltage** (the voltage required to sustain regular operation of devices) is another critical factor in determining the power consumption. Decreasing the operating voltage and the corresponding power consumption is an indispensable feature of wearable electronic devices.

It is noteworthy that the is the combination of the parameters above-mentioned that determine the overall performance of pressure sensors.

5.2.2 Transduction mechanism

Various transduction mechanisms exist for measuring a pressure by transforming a pressure stimulus into electrical signals (Lim et al.; 2005; Shirinov et al., 2008; Zhou et al., 2008). Among them, the most common include piezoresistivity, capacitance, and piezoelectricity. Each of these transduction methods has its own characteristics and features, with advantages and disadvantages. A scheme of transduction methods is reported in Fig. 5.1 (Zang, Zhang, Di, & Zhu, 2015), and a brief explanation of each will be discussed in the following.

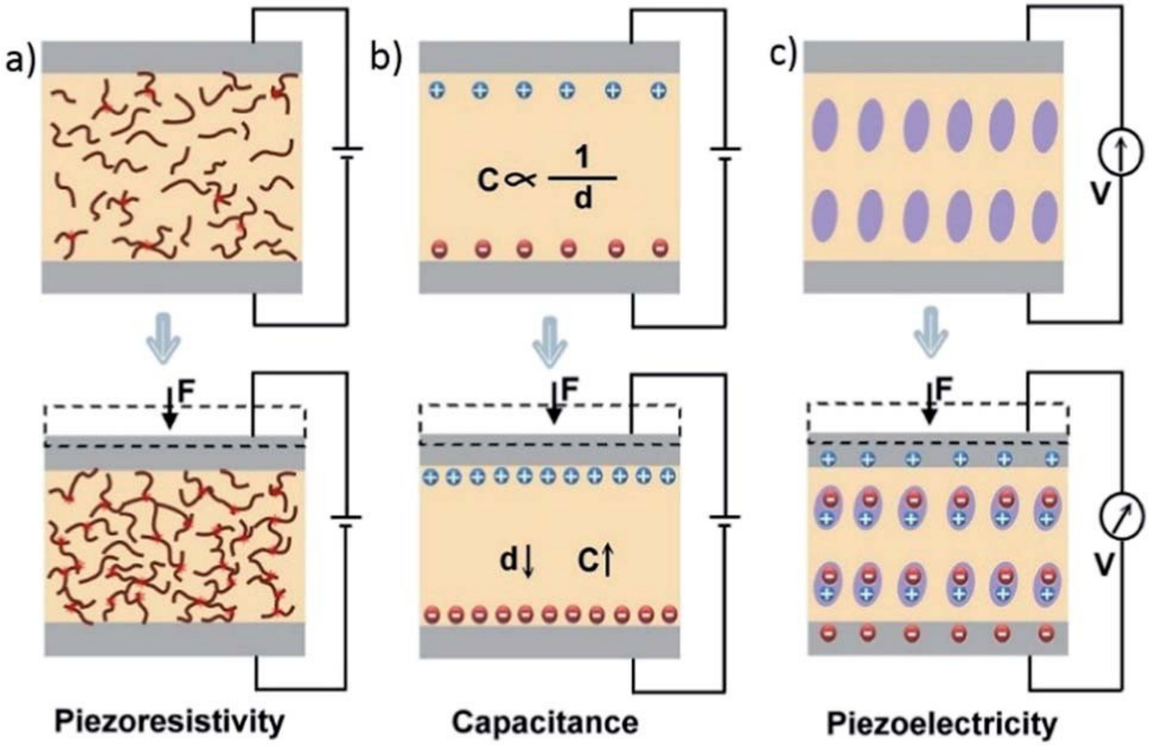


Figure 5.1: The schematic images of transduction methods: (a) piezoresistivity, (b) capacitance, and (c) piezoelectricity. From Zhang et al. (2015)

In general, as it will be described more in detail in the following, pressure transducers can be organized as a single-transducer sensor (for on-off applications) or in a multi-transducers matrix in such a way to get information on the particular pressure distribution of interest.

Piezoresistivity

The transduction principle of piezoresistive sensors is based on transducing the resistance change of a device into an electrical signal (Fig. 5.1a). The basic principle of the piezoresistive pressure sensor is to use a sensitive element made from a conductive material that changes its electrical resistance when it is deformed. Based on such physical phenomenon it is possible to associate a change in strain to an electrical signal, which is then (after suitable processing) converted to a pressure value. These sensors show simple device structures, easy read-out mechanism, and potential high pixel density (Pan et al., 2014). Piezoresistive sensors are suitable for use over large pressure ranges, making it possible to reliably measure large strains. The change in contact resistance between two materials, created by applied forces, is the main source of the electrical signal change (Choong et al., 2014). When a pressure is exerted on the device, the resistance of the pressure sensor changes accordingly. The existing power law, expressed as:

$$Rc \sim F^{-1/2}$$

ensures high sensitivity at low pressures and relatively large operating ranges for piezoresistive sensors. Furthermore, these devices generally exhibit a fast response speed.

Capacitance

Capacitance generally represents the ability to store electrical charge. In a common parallel plate capacitor, capacitance is given by the equation:

$$C = \varepsilon_r \varepsilon_0 \, A/d$$

where C is the capacitance, ε_r is the relative static permittivity of the material between the plates, ε_0 is the electric constant, A is the area of overlap of the two plates in square meters and d is the separation between the plates in meters (Hammock, Chortos, Tee, Tok, & Bao, 2013). Since the applied pressure causes the plate to deflect, a change in capacitance occurs. The pressure-induced capacitance change can be used to control the frequency of an oscillator or vary the coupling of an alternating-current signal through a network. Because of the relatively small change in the capacitance of parallel plates, these sensors tend to exhibit low sensitivity.

Piezoelectricity

Piezoelectricity is another commonly used transduction method for pressure sensors and refers to electrical charges generated in certain types of solid materials (such as crystals and certain ceramics) in response to applied mechanical stresses (Park et al., 2014). Because of their high sensitivity and fast response time, piezoelectric sensors are widely used in the detection of dynamic pressures such as vibrations (Hammock et al., 2013). Apart from utilizing a single piezoelectric material as a transducer, an integrating piezoelectric material with an amplifier element such as a transistor can also be used to construct flexible pressure sensors (Trung, Tien, Seol, & Lee, 2012).

Other transduction methods

In addition to the above-mentioned mechanisms, other transduction methods that convert pressure input into various signal outputs are also frequently used in pressure sensing technologies (Hammock et al., 2013). Optical pressure sensors, where light intensity and wavelength are used as a pressure signal (Ramuz, Tee, Tok, & Bao, 2012; Yun et al., 2014), resonant pressure sensors, where pressure-induced resonant frequency change is the essential transduction mechanism (Hammock et al., 2013), tribo-electric sensor which utilizes contact electrification to generate a voltage signal in response to a physical contact and so on.

5.3 Pressure sensors for Body-Seat contact pressure analysis

Given the recent advances in materials technology, flexible thin sensors have been developed for biomechanical applications and their use is widely reported in the literature (Andreoni et al., 2002; Kyung, Nussbaum, & Babski-Reeves, 2008; Marx, Amann, & Verver, 2005; Montmayeur et al., 2007; Na, Lim, Choi, & Chung, 2005; Verver, van Hoof, Oomens, Wismans, & Baaijens, 2004). They differ from general pressure sensors as they are typically used to measure the interface pressures between two relatively soft-objects. In fact, when we consider, for example, the measurement of interface pressures of a person sitting on a chair, the sensor needs to be very flexible to perfectly shape the curvature of the chair-body coupling and correctly measure the contact-forces. Furthermore, the sensors need to be sufficiently thin, as a thick sensor would significantly modify the specific measured coupling and give erroneous readings. Typically, in most applications these sensors have a thickness ranging from 0.1 to few mm (Ashruf, 2002). Moreover, in order to locally measure the pressure, the sensing area of each element should be as small as possible. Depending on the spatial resolution required for the specific application, sensing diameter ranges generally from 1 mm^2 to 100 mm^2 (Ashruf, 2002). General requirements for this type of sensors are high accuracy and reproducibility. The main applications for this technology are divided into two main categories based on the number of sensor elements used (i.e. a single sensor or an array of n-by-n sensors). Another classification is based on the number of output levels of the sensors: two levels sensors provides binary information on the basis of pre-determined pressure threshold (such as on-off switches), continuous scale sensors provide measurements on a large range of pressure values.

Examples of single-element applications are sensors for consumer electronics (volume controls, on-off controls), sensors for computer peripherals and musical instruments (keyboards, electronic drums and joy sticks), automotive sensors (seat occupancy detection, seatbelt tension measurement) and alarm sensors. In these applications, the sensors merely distinguish two states (on or off) and the demands on the performance are generally lower than that of the digital or analogue sensors. Examples of continuous sensors are robotic touch and picking sensors and load cells, shown in Fig. 5.2.

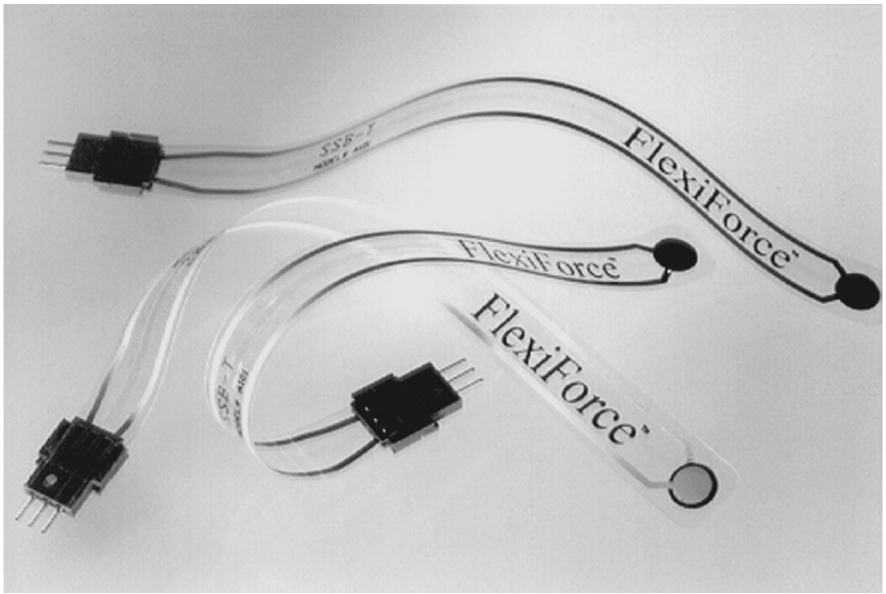


Figure 5.2: Flexible force sensor from Tekscan. The single sensing element is circular and located at the tip of the sheet. Photo from Ashruf (2002)

Sensor arrays are instead usually obtained by ordering the single elements in a matrix structure where the sensor is the result of the crossing of rows and columns, as shown in Fig. 5.3. The first cells of all elements in a row are connected and similarly the second cells of all elements in a column are interconnected. In this way, an n-by-n array has n-by-n leads out and are usually connected to multiplexers or by using common grounds in order to reduce the number of leads out.

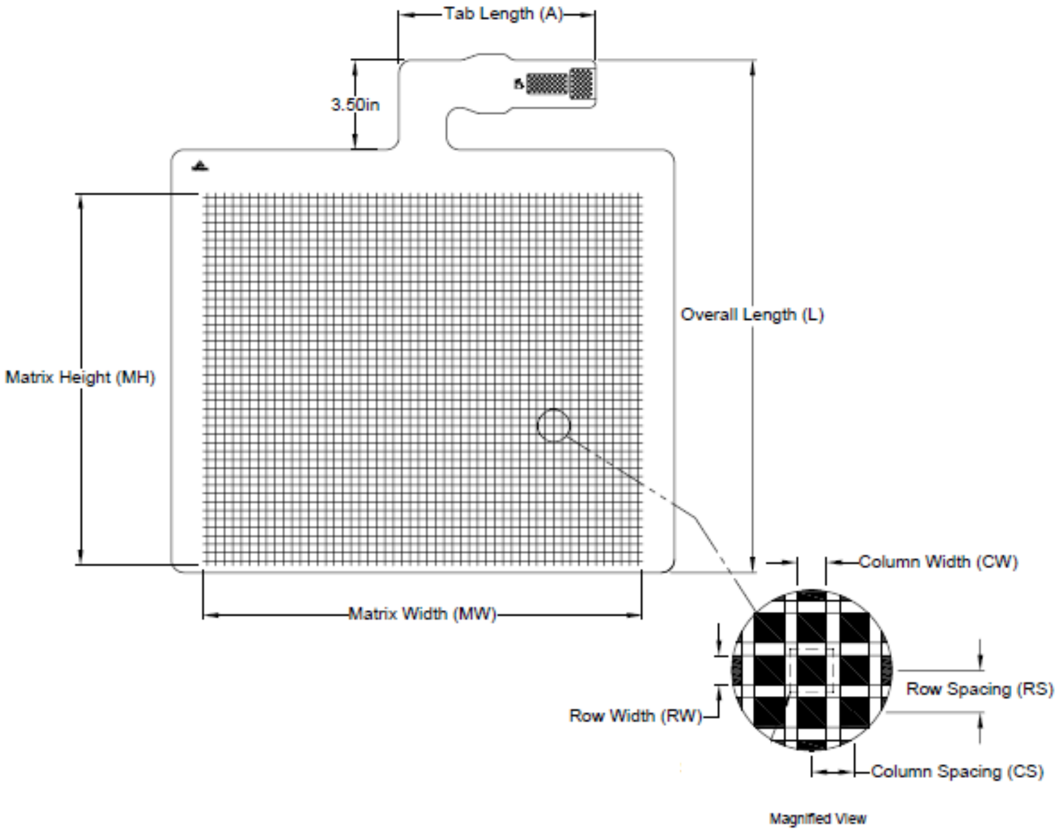


Figure 5.3: Structure of a pressure sensitive mat: it is possible to see the matrix structure with rows and columns.

Arrays sensors technologies are typically integrated in three-layer configurations: the outer layers are made of flexible (polymer) materials covered with conductive lines, while the inner layer is composed by the force sensing material (conductive polymer sheet/ink or non-conductive elastomer dielectric).

Examples of these sensor arrays are pressure mapping systems for measuring body-seat interface pressures in wheelchairs or beds, car seats while driving (Kyung and Nussbaum, 2008) or office chairs. They are coupled to a read-out electronics which is then connected to a computer, usually via USB interface. Using dedicated software, the pressure data is scanned real-time and displayed on a computer screen in 2-D color pictures or 3D graphs. Data analysis tools allow the extraction of time-series for many parameters. Usually, the peak and mean pressure, center of pressure or force, contact area can be easily obtained (Fig. 5.4). Depending on the particular application, there is a wide choice in operating range. For example, pressure mapping systems for seats typically have a range up to 0.04 MPa, while measurement systems for automotive brake pads have a range of up to 175 MPa.

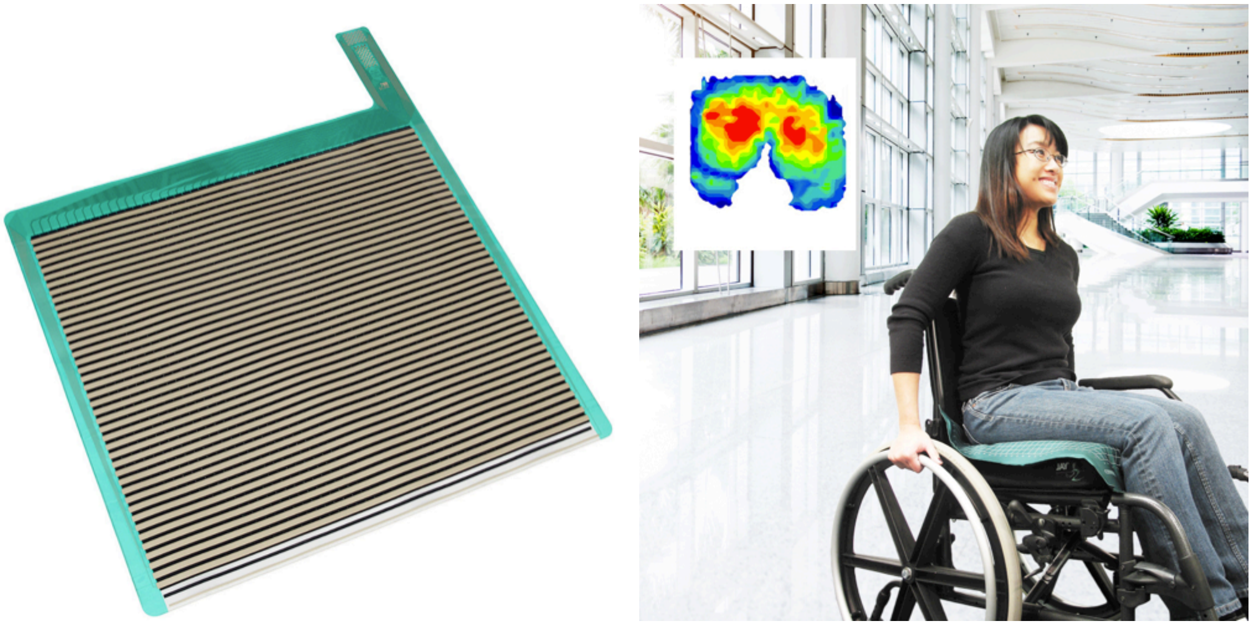


Figure 5.4: Left) A pressure sensitive generally used in ergonomics. Right) An example of a pressure mat measuring seat-contact pressure in wheelchairs.

5.4 Thin-flexible sensors technology

As for general pressure sensors, different technologies are available to build for flexible sensors: piezo-electric, pneumatic, hydraulic, resistive and capacitive. The piezoelectric method is not suited for static measurements because of its leakage current. In fact, in case of a constant load applied to a piezoelectric sensor for an extended period of time (for example a patient lying in bed or sitting for many hours) the response would gradually decrease in time approaching low or null values. The pneumatic and hydraulic methods require quite complicated set-up and result in a relatively large thickness (Gyi et al., 1998), not recommended for biomechanical applications. Currently, the most used methods are the resistive and capacitive ones, and the following considerations will be limited to these two technologies. The former is based on the resistance change of a piezoresistive layer when a force or pressure is applied, and is characterized by a simple read-out circuitry. The capacitive method is based on changes in capacitance between two parallel plates which occur when a force or pressure is applied. In this case, the output is less sensitive to temperature and humidity.

5.4.1 Differences between piezoresistive and capacitive

Most manufacturers have adopted the piezoresistive read-out technique because it is straightforward and relatively simple, being the resistance changes quite large. This technique is also relatively insensitive to the presence of electromagnetic fields. The capacitive measurement technique provide a lower output signal than the resistive one and requires the presence of an embedded amplifying circuitry, thus making more complicated the overall setup. For this reason, the resistive technology is usually considered more suitable to be applied for thin and flexible pressure sensors, which are employed in several common ergonomics and biomechanical applications.

Nevertheless, resistive sensors exhibit also some disadvantages. Typical issues of resistive sensors are their non-linearity and the complex dependence of the response on number of pressure cycles and history (hysteresis). For this reason, these sensors need to be “conditioned'' before the use. The technology of some manufacturers also suffers from the dependence of the sensor response on temperature and humidity, poor stability and limited durability. Since both types of sensors have advantages and disadvantages, the choice on the most appropriate technology highly depends on the application, even though both technologies are considered interchangeable for several applications both are currently widely used for clinical and research applications.

5.4.2 Limitations

As previously mentioned, an important limitation of all flexible thin piezoresistive pressure sensors is hysteresis. In fact, compared to their rigid counterparts, these sensors exhibit relatively high hysteresis (values of typically more than 5%). This is a consequence of the presence of polymers, which are required to ensure flexibility and elasticity but unfortunately such features involve the existence of high hysteresis. Another limitation refers to the presence of creep (the variation of the output at constant load), which is also typical of many polymers. These properties contribute to the relatively high inaccuracy (typically 5÷10%) compared to conventional non-flexible sensors such as, for example, those used in pressure or force platforms. Generally speaking, an ideal sensor response should be linear with respect to the measured parameter but flexible sensors, as previously mentioned, generally exhibit a non-linear behavior. However, despite such important limitation, the usefulness of thin flexible sensors is not questionable: we can imagine, in fact, a wide list of applications in which conventional rigid sensors are simply not applicable because of their size and (fixed) shape and the use of flexible sensors is unavoidable.

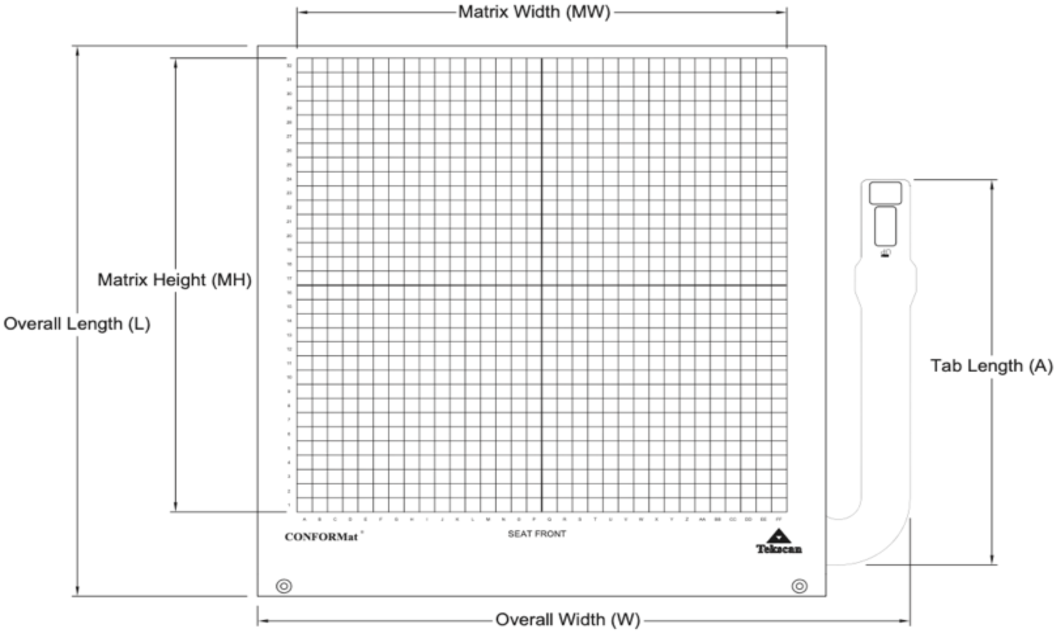
On the other hand, some of the limitations of flexible sensors can be, at least partly, overcome using suitable calibration procedures, and most suppliers advise regular calibration of the systems to maintain the accuracy within an acceptable range.

Different manufacturers of piezoresistive flexible sensors usually have their own patented technologies but, as previously mentioned, the most widespread technology uses two thin flexible polymer sheets with screen printed (thick film) or deposited (thin film) conductive lines. The conductive interconnection patterns can be either applied to one single sheet, resulting in a planar wiring configuration, or applied to both sheets, resulting in more flexible wired configurations. Depending on the specific manufacturing technology used there are sensors only suitable for qualitative pressure evaluations (i.e. Interlink and IEE), or quantitative pressure/force analysis giving exact pressure measurements (i.e. Tekscan).

Tekscan Body Pressure Mapping Sensor

Among the different options available on the market, the Tekscan (Tekscan Inc, Boston, USA) systems have been widely used in many studies aimed to investigate seat-body contact (Andreoni et al., 2002; Ebe & Griffin, 2001; Horváth et al., 2017; Kyung et al., 2008; Podoloff, 1993). Such systems guarantee reliability, high accuracy and easiness of use with affordable price. For these reasons they have also been used in the present work.

The mapping sensor is composed by a thin pressure-sensitive array matrix obtained by intersecting rows and columns of conductive material, and uses the 3-layer configuration previously described. When pressure is applied to the sensing area, the resistance of the of the sensing elements (named Sensels™) changes. These sensors can be used in a single or two-mat configuration to evaluate pressure at the occupant-seat interface. The single-sensor configuration is used to evaluate either the pressure distribution on the backrest or on the



General Dimensions					Sensing Region Dimensions						Summary	
Overall Length *L*	Overall Width *W*	Tab Length *A*	Matrix Width *MW*	Matrix Height *MH*	Columns			Rows			Total No. of Sensels	Sensel Spatial Resolution
					CW	Pitch *CS*	*Qty.*	*RW*	Pitch *RS*	*Qty.*		
(mm) 571.5	(mm) 627.4	(mm) 400.3	(mm) 471.4	(mm) 471.4	(mm) 6.4	(mm) 14.7	32	(mm) 6.4	(mm) 14.7	32	1024	(sensel per sq-cm) 0.5
(in) 22.50	(in) 24.70	(in) 15.76	(in) 18.56	(in) 18.56	(in) 0.25	(in) 0.58	32	(in) 0.25	(in) 0.58	32	1024	(sensel per sq-in) 3.0

Pressure Ranges

kPa	34
psi	5

Figure 5.5: Tekscan 5330E datasheet.

seatpan, while the two-sensors configuration is used to evaluate both simultaneously. The scanning electronics connected to the sensor collects resistance changes and convert them into a digital signal, which is then transmitted to a computer for real-time analysis. This kind of sensors is available in different shapes and sizes and can operate in different pressure ranges (from 0-14 kPa to 0-207 MPa) depending on the specific application. Their physical characteristics allow to directly instrument the impact surface, without altering the interface features, resulting in high accuracy on pressure contact information.

5.5 Tekscan 5330E

The specific sensor used in the present study is the Tekscan 5330E (Tekscan Inc, Boston, USA) whose datasheet is reported in Fig. 5.5. This pressure-sensitive mat was chosen due to the high accuracy, absent or low drift of the signal over time and because of its large use in past studies, with high reliability. It works in a 0-34 kPa range and is composed by a 32x32 sensors matrix, resulting in 1024 sensor units in total. A resume of typical workflow of the used pressure sensitive mat is explained in the following:

- Resistance of the sensing elements (Sensels™) varies inversely with applied load.
- Sensor output is linearized into digital counts or “raw” values on a scale ranging from 0 to 255.
- Calibration converts raw values into engineering units, such as psi, kPa, mmHg (Fig. 5.6).

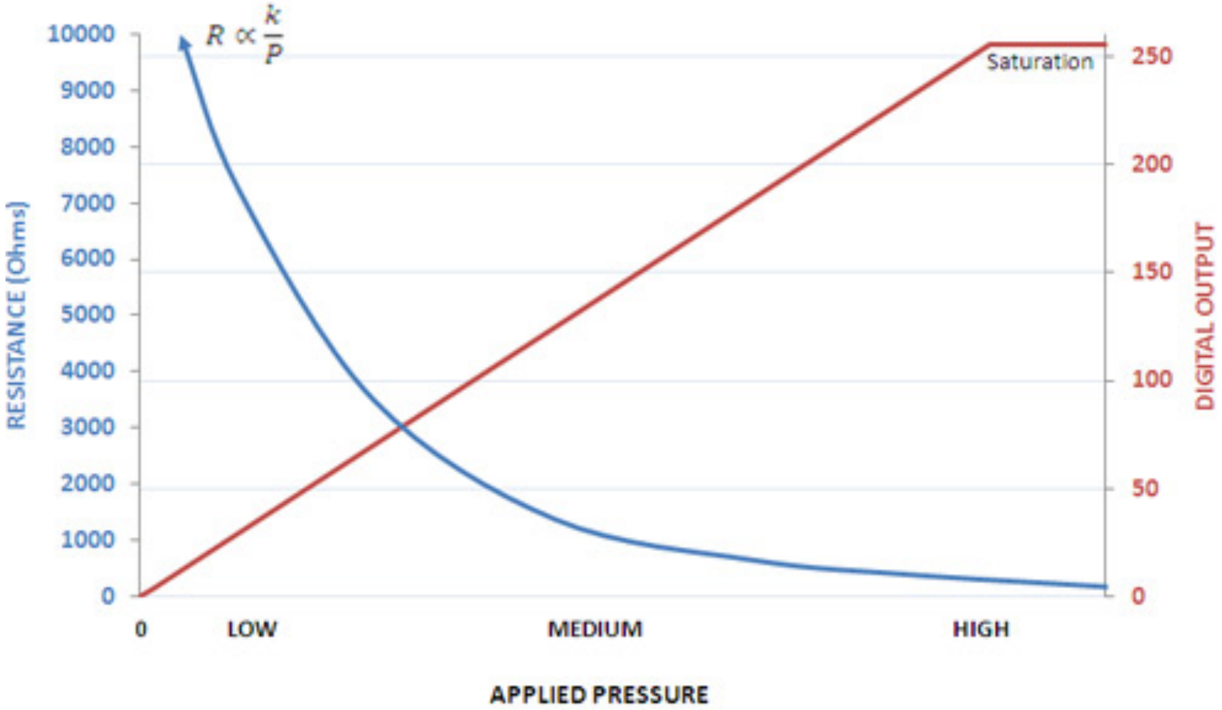


Figure 5.6: An example of the Tekscan 5330E calibration curve.

5.5.1 Data acquisition electronics

The Tekscan pressure mapping sensors employ a microprocessor-based circuitry to control scanning frequency, adjust sensitivity and optimize the performance of matrix-based sensors. Fig. 5.7 shows a simplified electrical schematic of the employed 8-bit electronics with 255 levels, that scans the intersecting points of the sensor’s rows and columns and measures the resistance at each crossing point or sensing element (Sensel^{TM}). The Sensels^{TM} are read in the presence of multiple contacts; each Sensel^{TM} can be represented by a variable resistor whose value is the highest when no force is applied.

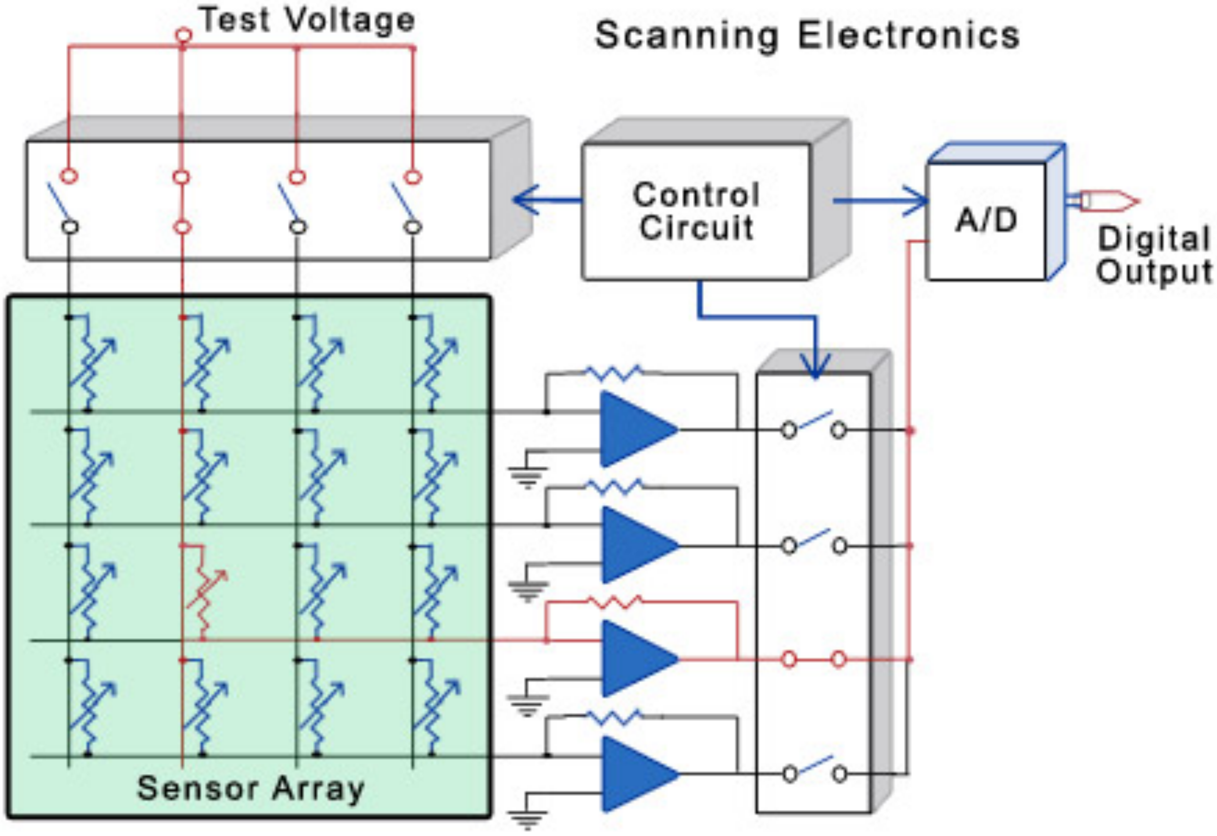


Figure 5.7: An example of the microprocessor-based circuitry that controls Tekscan system.

The external scanning electronics (represented in Fig. 5.8) consist of a cuff used to transmit data from the sensor to the hub, which, in turn, acts as a gateway between the cuffs (and attached sensors) and the PC or laptop computer. This system is powered by a standard AC adapter; on one end cables leading to cuffs are connected, on the other end a single USB cable leads to the PC (or laptop computer). Multiple handles can be used simultaneously depending on the experimental set-up (with single or multiple sensing devices). Indicators on the handle show system status and allow a doublecheck control of data collection. Handles are powered directly from PC via USB cable and can be set up to 100 Hz scanning speed varying on sensor type and model.

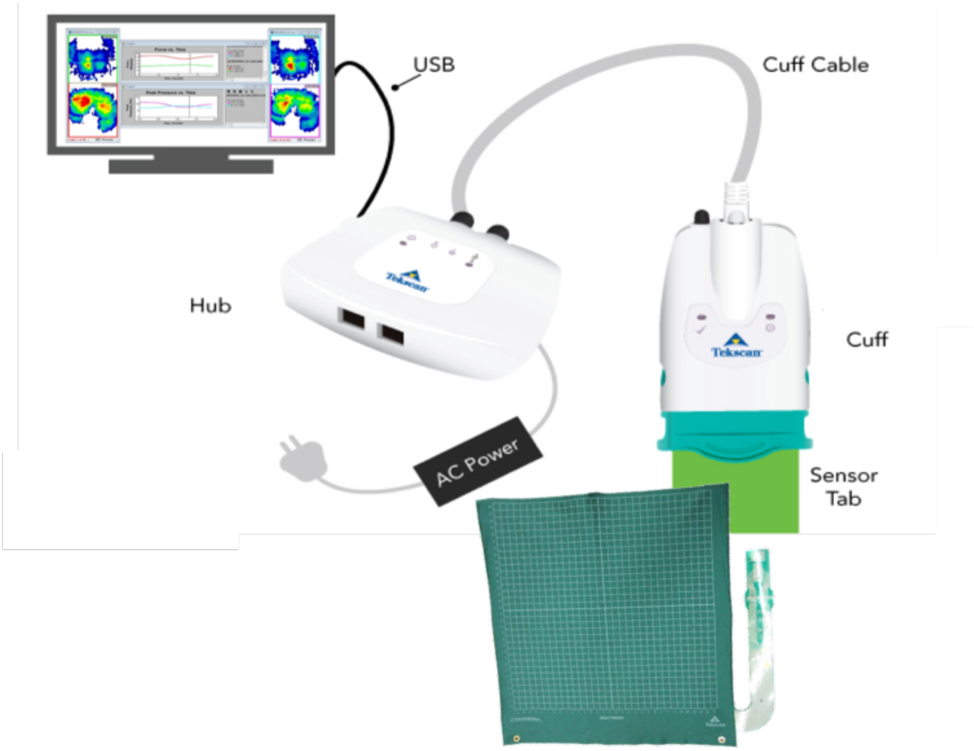


Figure 5.8: Schematic representation of the Tekscan external scanning electronics connected to the PC and to the sensing unit

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Chapter 6

Experimental protocol for Sitting Postural Strategies evaluation

The focus of this chapter is to describe the protocol used to assess the specific postural strategies adopted during the cases of prolonged sitting investigated in the present study. In particular, the task procedure and the setup used for the task acquisition will be described in detail, as well as the data processing techniques.

Then, the data processing methods are described, as well as the considered sway parameters and in chair movements calculation algorithms used in this study. Details about participants and used tools are also provided in the following chapters.

6.1 Introduction

As mentioned in Chapter 3, in ergonomics research the evaluation of (dis)comfort can be supported by different objective methods and, in particular, pressure-sensitive mats represent a suitable tool to obtain information that can be matched with perceived discomfort on the basis of information on body–seat interaction. In literature, several methods have been proposed to detect the existence of a relationship between changes in posture and perceived discomfort (Fasulo, Naddeo, & Cappetti, 2019; Le et al., 2017; Na, Lim, Choi, & Chung, 2005). In particular, as it will be further described in this chapter, starting from raw pressure data, it is possible to obtaining a set of parameters which can be considered useful and reliable for discomfort characterization purposes.

6.2 Experimental design

6.2.1 Sitting posture monitoring test

The evaluation of pressure distribution, and subsequent assessment of postural strategies adopted during long-term work-shifts, was performed having participants sat at their workstation (either desk or cockpit depending on the specific case-study) which was equipped with the instrumentation (Fig. 6.1) previously described in Chapter 5. It is noteworthy that all the experimental tests described in the present dissertation, have been performed under actual working conditions. Indirect information on workers' posture and discomfort (obtained by means of a pressure sensitive mat and subjective discomfort questionnaires) were in this way assessed in their usual working context, so as to obtain data referring to real conditions, thus including the environmental variables which characterized the analyzed task.

Upon arrival at their usual workplace, participants signed an informed consent form and demographic and anthropometrics data were collected (age, height, weight and years of experience).

Participants were then asked to set the workstation on their preferred settings (the one they use every day while working); after that, the pressure sensitive mat was placed on the chair or seat cushion-pan.

Figure 6. 1: An example of the workstations equipped with the pressure sensitive mat system. On the left the bus cockpit, on the right the office workers' desk.

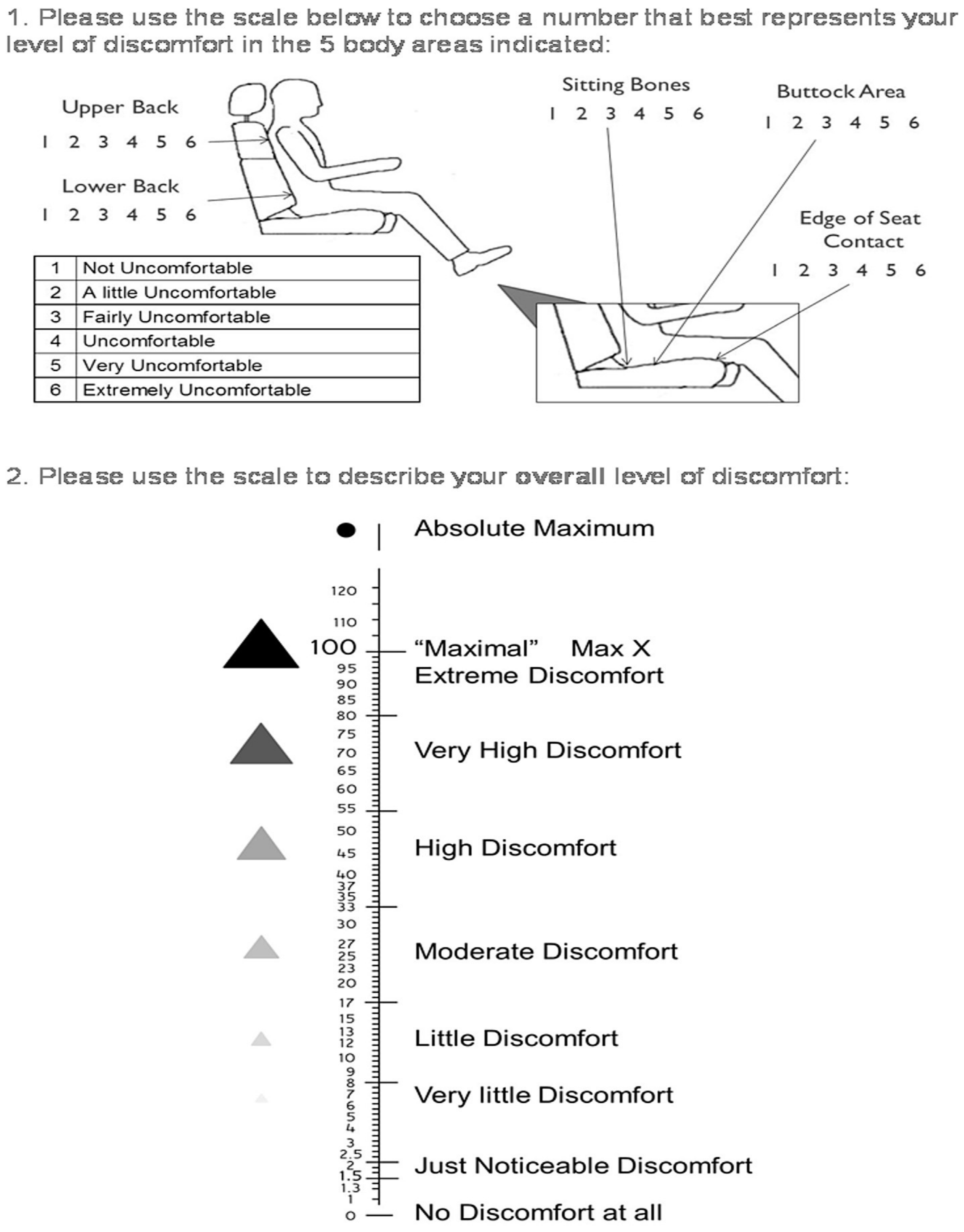
Subjects were then instructed on how to complete the perceived discomfort survey (Fig. 6.2), which was administered at regular time intervals during the testing sessions (Borg & Borg, 2002; Sammonds, Fray, Mansfield, 2017).

Prior to start the data collection, participants were also asked to sit and make the final adjustments on their workstation (seat height, backrest inclination, distance to steering wheel/desk etc.) and the sensor calibration procedure, further described in the following, was performed. Participants were also required to sit using seat back and arm-rests, while the operator started the data acquisition via software. They were asked to not change workstation settings within the entire duration of the test session.

Contact pressure data were continuously recorded for all the work-shift, or previously scheduled test duration, during a regular scheduled work-shift. During the test, participants were allowed to take short breaks if needed: they were asked to stay seated unless they needed a break or they had scheduled rest breaks to follow (i.e. at the bus terminal).

6.2.2 Participants

In this study, two categories of professional workers exposed to prolonged sitting (office workers, drivers and quay crane operators) were recruited on a voluntary basis. The sample size for each study was similar to those of previous studies. Each participant was informed about the study purposes and signed a written informed consent in accordance with the 1964 Helsinki Declaration and its later amendments. Groups‘ characteristics as well as set-up experiment configurations used to evaluate sitting behavior and strategies will be extensively described in the following dedicated chapters.



1. Please use the scale below to choose a number that best represents your level of discomfort in the 5 body areas indicated:

1	Not Uncomfortable
2	A little Uncomfortable
3	Fairly Uncomfortable
4	Uncomfortable
5	Very Uncomfortable
6	Extremely Uncomfortable

2. Please use the scale to describe your **overall** level of discomfort:

Figure 6. 2: Perceived discomfort survey. Part 1 includes the discomfort scale defined in ISO 2631-1 and a description of the body parts. Part 2 includes the adapted Borg CR100 scale (Borg and Borg, 2002).

6.2.3 Body-seat pressure data collection

Body-seat contact pressure data collected in this study was carried out using one or two pressure sensitive mat (Tekscan 5330E) placed on the subjects' seat in order to continuously record contact pressure distribution during the trial. The mat was placed in such a way to cover all the seat-pan area and avoiding creases, which can result in high pressure points and lead to an altered measurement. In order to prevent the mat from slipping or moving during the tests, it was secured to the seat by means of special straps. Before sitting, subjects were asked to empty their pockets to avoid any "false" high peak pressure point.

The dedicated CONFORMat Research 7.20 software provides a real-time dynamic image of the pressure distribution, through a false color scale as shown in the Fig. 6.3 (the blue color indicates a lower pressure, while the red indicates a higher pressure). The rhomboid symbol indicates the point where the resultant of all contact forces is applied, namely the center of pressure (COP).

The following preliminary operations were performed before each test:

- the hardware components were connected, and their correct functionality was assessed;
- by means of the CONFORMat Research 7.20 software, the operator set the main acquisition parameters such as the measurement units (length, force and pressure) duration of the recording (length of the movie in real time), number of frames to record, and either the period (elapsed time between frames) or frequency (frames per second), have been set before each trial according to the following equation:

$$(Frequency * Duration) + 1 = Frames\ to\ Record$$

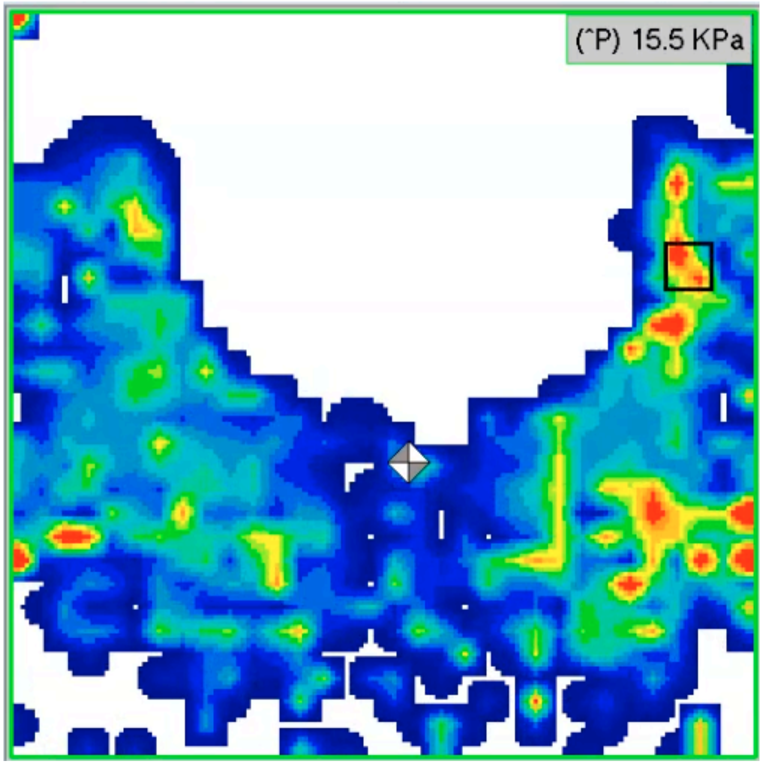


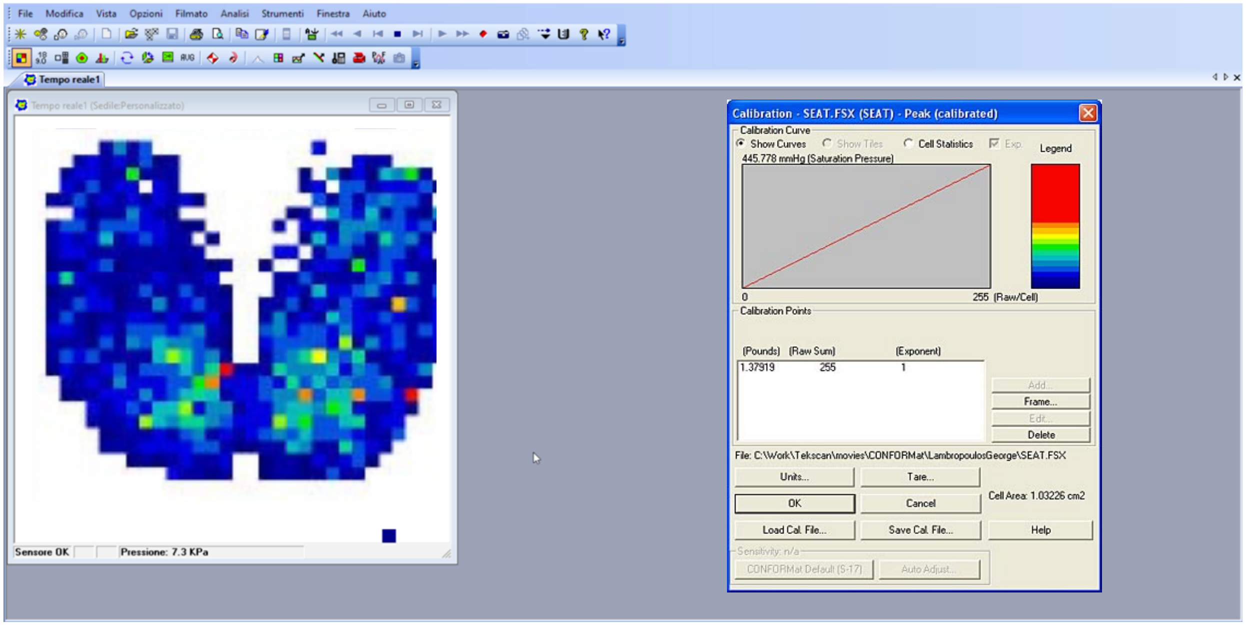
Figure 6.3: Example of the false color scale representing the dynamic image of the pressure distribution.

- a calibration procedure was performed in order to convert the raw digital output of the sensor into an actual engineering unit, such as *psi* or *kPa*. Before a calibration is performed, the data from the sensor is in fact shown as a raw sum of digital counts values in the real-time window status bar of the software, in a scale ranging from 0 to 255.

Force Calibration There are two native methods available to calibrate the sensors: linear calibration and 2-point power law calibration. In the present study configuration, the linear calibration has been performed and the following description will be limited to this procedure.

This choice was done as the one point calibration is faster to perform and is considered to be sufficiently accurate for tests where the applied load has a limited range (Gillis, 2005), as the case of this study. In tests with large load variations, a “2-power law calibration” is more recommended. This calibration would require the user to load the sensor with two known loads at 20% and 80% of the expected maximum test load, with a delay between the two phases of at least 2 minutes, resulting in a relatively long protocol for a field study.

According to the manufacturer’s prescription, the linear calibration procedure requires that the subject sit on the sensor. His/her entire weight must be loaded on the sensor and thus arms, legs and back should be suspended and not in contact with any external entity. As the results may be inaccurate if the subject fidgets too much during the calibration, he/she is also required to stay as still as possible. Before starting the actual calibration, the operator wait 90-120 seconds to allow the sensor to become accustomed to the applied weight. This phase, called "settling"



Sensore OK

Pressione: 7.3 KPa

● Show Curves ○ Show Tiles ○ Cell Statistics ☑ Exp.

445.778 mmHg (Saturation Pressure)

(Pounds)	(Raw Sum)	(Exponent)
1.37919	255	1

File: C:\Work\Tekscan\movies\CONFORMat\LambropoulosGeorge\SEAT.FSX

Cell Area: 1.03226 cm2

Figure 6. 4: Example of the software interface. The right window shows the calibration curve. On the left panel the calibrated mat is visible.

period, is also necessary whenever the sensor is unloaded for long times and then reloaded. After this phase, it was possible to run the calibration, which only takes up to 2 seconds, and begin with the test recording. Figure 6.4 shows an example of the calibration window along with the representation from the calibrated mat.

Recording Once all the recording parameters had been set, and the calibration has been successfully performed, the sensor is ready to record data. Recording of contact pressure was performed by means of the dedicated CONFORMat Research 7.20 software.

Subjects were instructed to sit as they normally would have to perform their activity, acting in a consistent and as natural as possible manner. Data were sampled at a 10Hz frequency and, when the desired number of frames was collected (in general, at the end of the work-shift), recording automatically stopped. It was always possible to stop recording before this time, if necessary. Collected pressure data were stored on the personal computer and are available for further review, analysis and postprocessing.

6.2.4 Subjective discomfort ratings

Subjective methods of discomfort analysis were also employed to evaluate the existence of possible relationship with data obtained from objective assessment. Perceived discomfort was assessed at regular time intervals using a two-parts questionnaire adapted from the Borg CR100 scale (Borg & Borg, 2002). In all studies participants were asked to rate their perceived discomfort subjectively at regular time intervals. Questionnaire responses were reported verbally and, according to literature (Sammonds, 2015; Sammonds et al., 2017) participants were asked to provide first rate on local discomfort (body part discomfort) and then overall discomfort (overall perceived discomfort). The used questionnaire (Fig. 6.2, Sammonds et al., 2017) is composed as follows:

- Part 1 focuses on local discomfort. In particular upper back, lower back, sitting bones, buttock area and edge of the seat contact body regions were included in the 6-point discomfort scale based on ISO 2631-1-2003 guidelines;
- Part 2 describes the overall discomfort. The adapted CR100 scale ranges between 0 and 120, and incorporates verbal cues in order to help subjects to better understand the meaning of the intensity levels; triangles increasing in size and blackness congruently with the values of the verbal descriptors developed form the overall discomfort scale proposed by (Reenen et al., 2008)(Sammonds, 2015).

6.3 Data Processing

Panes The software allows to virtually divide the pane in four sub-panels by acting in the so-called panes were placed in the recorded movies and used to display data for specific areas of the sensor. This allows analyzing pressure distribution across different body regions in contact with the seat, such as thighs and gluteus. In our case, the mat area was divided into four panes as shown in Fig. 6.5.

After this process, it was possible to display and analyze data inside a pan separately from the rest of the window's data (i.e. right and left thighs, and right and left gluteus areas).

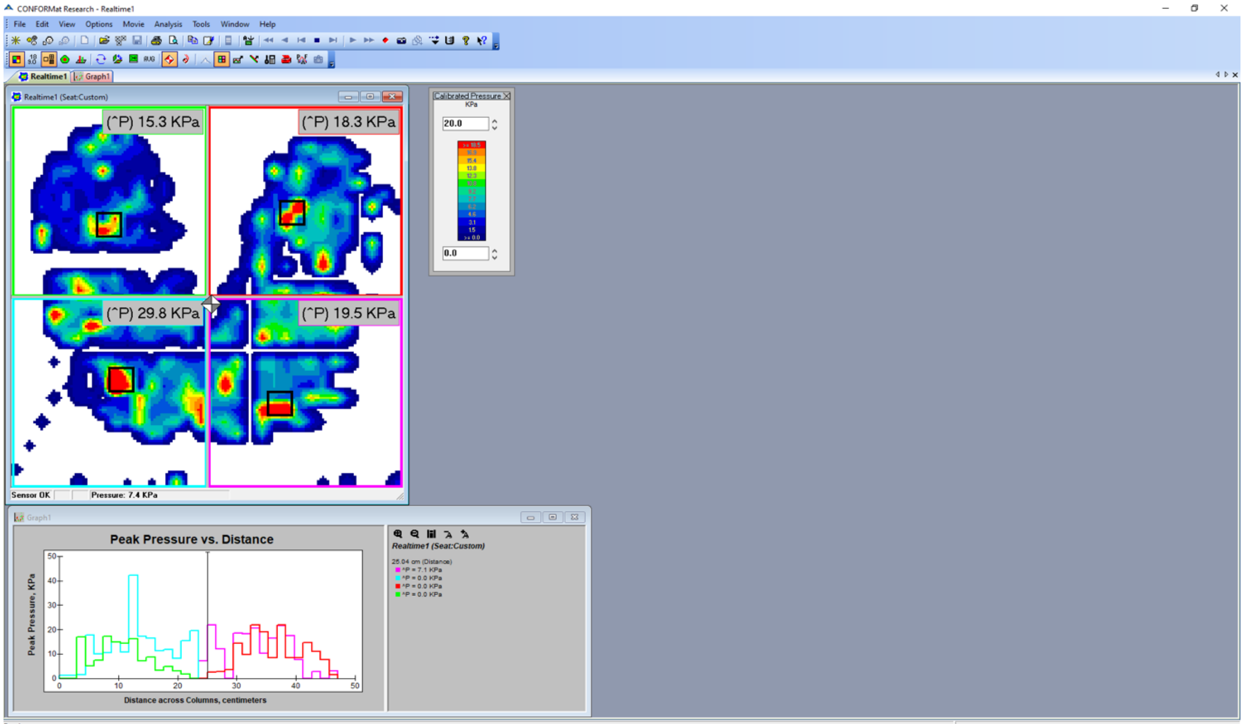


Figure 6.5: Software interface showing the mat area divided into the four quadrants of the gluteus and thighs areas. Graph on the bottom reports the real-time peak pressure values recorded on the four areas

6.3.1 Data Export

Time series of interest parameters referred to the overall test were exported as an ASCII (.txt) file. In particular, the following data were extracted with the software (Fig. 6.6):

- Center of Pressure (**COP**) coordinates: are the x-y coordinates (on the mat reference system) of the point of application of the resultant of all the contact forces acting on the sensor in each frame of the dataset. The graphic representation of the COP trajectory provides a visual description of the movement of the COP during the trial.
- Contact Area (**CA**): is the sum of the areas of the elements of the mat involved in the contact (i.e. measuring non-zero pressure). Contact area represent a measure of the extension of the body-seat contact region:

$$CA = \sum_{i=0}^{n} A_i$$

where A_i is the area of the i^{th} sensing cell and n is the number of loaded cells;

- Mean Pressure (**MP**): pressure on the loaded or "contact" cells inside the whole mat area or single panel (left and right thighs and gluteus), which is calculated by dividing the total force by the "contact" area:

$$MP = \frac{\sum_{i=0}^{n} F_i}{CA}$$

where F_i is the contact force on the i^{th} cell;

- Peak Pressure (**PP**): highest value of pressure in a frame inside the whole mat area or single panel

$$PP = MAX\left\{\frac{F_i(t)}{A_i}\right\}$$

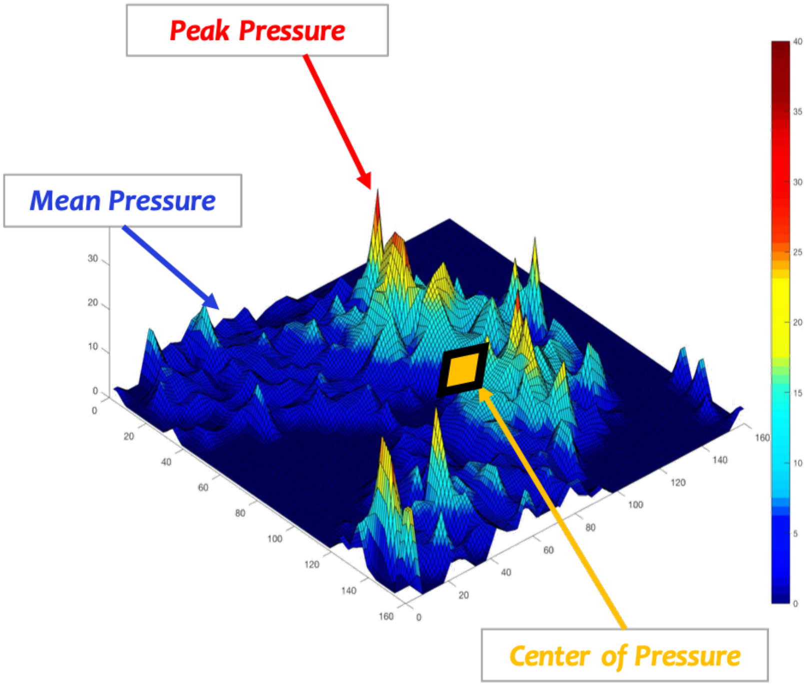


Figure 6.6: 3 -D representation of interface contact pressure. Interest variables are indicated by arrows: peak and mean contact pressure, along with COP coordinates.

6.3.2 Post processing

Exported data were further post-processed by means of a custom code developed under the Matlab environment (MathWorks Inc, Natick, USA). Firstly, COP trajectories were low-pass filtered before further calculations (4th order zero-lag Butterworth filter, cut-off frequency of 4 Hz), to avoid any noise artifact (i.e. due to external vibrations). The shift breaks (either unpredicted or scheduled) were automatically detected by setting a threshold value for the average contact pressure value and time (number of seconds where the pressure value was below the defined threshold) and associated data discarded. In particular, we considered a break (and thus not processed) a period during which the average pressure value was lower than 20% of overall mean pressure for more than 30 seconds. Break information (duration, start time, end

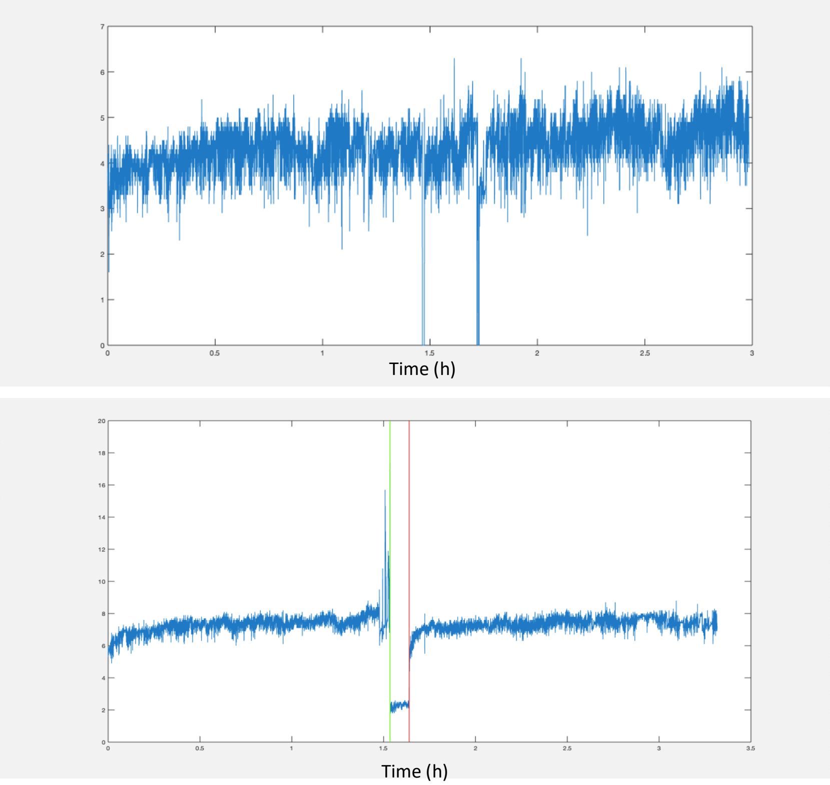


Figure 6. 7: Mean pressure time series representation. The bottom graph shows an example of pauses calculation: the green line marks the pause start, while the red line indicates the pause end.

time) were saved in a .txt file. An example of break calculation can be seen in Fig.6.7. The developed software allowed also the calculation of the task-induced trunk sway and the number of In Chair Movements (ICM) performed during the trial.

Sway parameters

The following sway parameters have been calculated and considered in the different studies of this thesis work (a graphic explanation is shown in Fig. 6.8):

- *Sway path* (SP): is the overall distance travelled by the COP during the trial expressed in mm. This is approximated by the sum of the distances between consecutive points on the COP path;
- *Sway area* (SA): is the area of the 95% bivariate confidence ellipse, which is expected to enclose approximately 95% of the points on the COP path (mm^2);
- *COP maximum displacements* (the difference between the maximum and minimum values of the selected coordinate recorded during the trial, mm) in the antero-posterior (AP) and medio-lateral (ML) directions;
- *COP velocity*: it is calculated as the average of the instantaneous values recorded during the trial ($mm\ s^{-1}$) in the AP and ML directions. This parameter normalizes the total excursions of the COP to the analysis interval. The COP time series are filtered in this way to the frequency range of interest to minimize the quantization noise that may inadvertently inflate measures such as mean velocity and total excursions (Prieto et al., 1996);
- *Ellipse's centroid* (EC) coordinates;

- *EC velocity*: calculated as the average of the EC instantaneous velocities recorded during the trial (mm s^{-1}) both in the AP and ML directions.

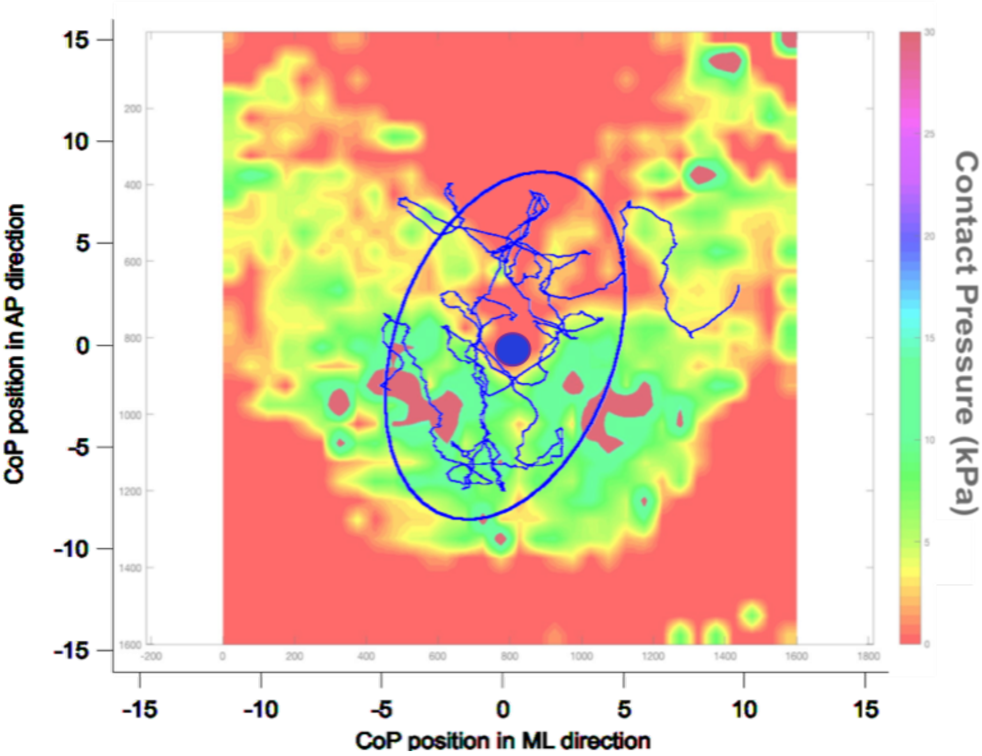


Figure 6.8: representation of pressure distribution on the seat along with a schematic figure of the sway parameters. In particular, COP sway, confidence ellipse and its centroid are shown.

In Chair Movements

The number of fidgeting or in chair movements (ICM), was quantified using the displacement of the sway ellipse's centroid EC (a graphical example is shown in Fig. 6.9). This choice was made basing on a pilot study described in detail in Chapter 7. In particular, an ICM occurred when the EC displacement, calculated across two consecutive 2.5-sec windows, exceeded a predefined threshold, chosen by mean of an iterative method, better described in Chapter 7.

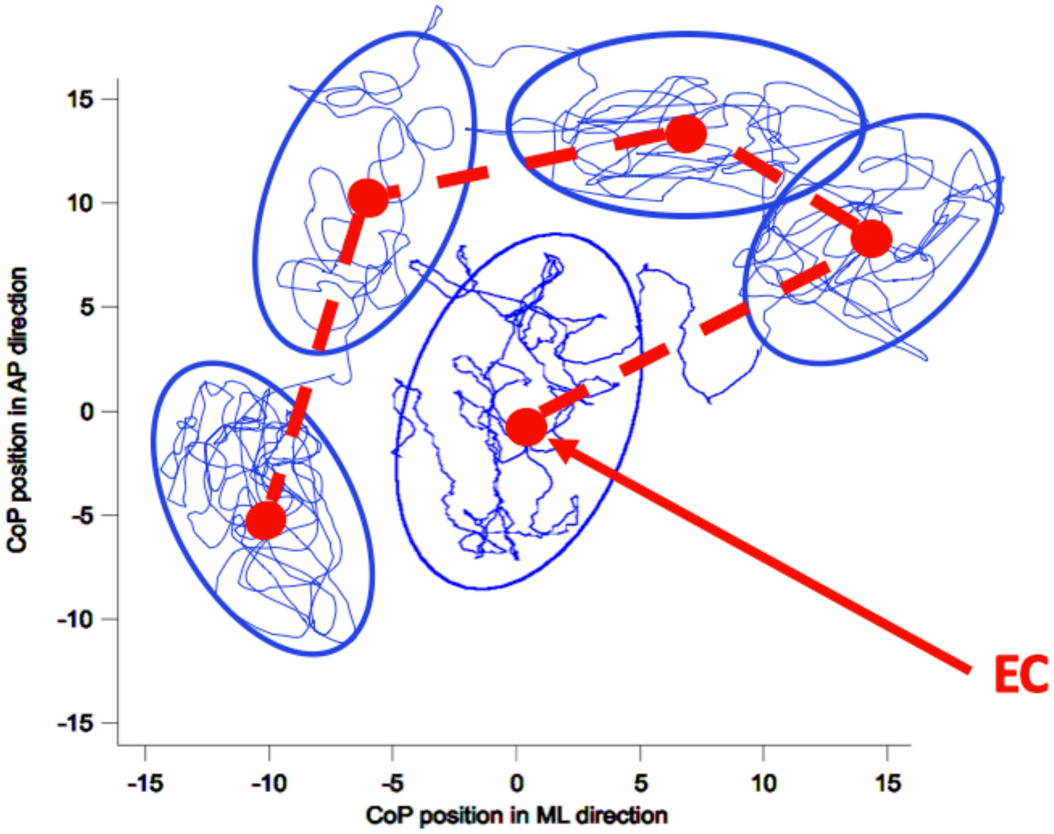


Figure 6.9: Schematic representation of the algorithm used to calculate ICM. In particular, COP sway path and confidence ellipses (each referred to a 2.5 sec window) are shown. The distance between EC is highlighted by the discontinuous red lines.

6.4 Statistical analysis

The Statistical Package for Social Sciences (SPSS Statistics, IBM) was used for data analysis. The level of significance was set at $p < 0.05$. Data analysis will be described in detail in each chapter, according with the characteristics of the investigated population.

Generally, demographic data, clinical and kinematics characteristics were firstly described with descriptive statistics, using mean and standard deviation. Differences between groups for the investigated features as well as relationships between discomfort and sway and ICM data were assessed with parametric or non-parametric tests, in accordance with the data distribution.

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Chapter 7

Pilot Study for the selection of *ICM* Calculation Algorithm

As described in Chapter 3, discomfort/fatigue while sitting is associated with “macroscopic changes” in posture that are described in the literature as “*In Chair Movements*” (ICM). While several studies agree on the existence of such association, a generally accepted method to objectively quantify ICM still doesn’t exist. Several algorithms proposed in literature (Cascioli, Liu, Heusch, & McCarthy, 2016; Le et al., 2017; Na, Lim, Choi, & Chung, 2005) calculate the number of In Chair Movements basing on raw body-seat contact pressures or contact forces values. This choice, although proven to be reliable in laboratory tests settings, might not be suitable under actual conditions, especially in dynamic environments such as vehicles, where a pressure change does not necessarily reflect a macro-movement of the body over the seat. In fact, especially when driving on urban roads, the occurrence of sudden random acceleration peaks or vibrations caused by the road conditions, may be mistakenly classified as ICM. Thus, the purpose of this pilot study was to propose a reliable algorithm able to detect a postural shift (or change in posture) in both laboratory and field test settings.

7.1 Participants and Methodology

The sample consisted of 5 volunteer participants from the staff and students of Cagliari University, recruited at the Biomechanics and Industrial Ergonomics Laboratory. Anthropometrics and demographic data on subjects are reported in Tab. 7.1.

Table 2: Anthropometric and demographic data of the 5 subjects who participated in the pilot study. Mean ± standard deviation values are reported

	Mean ± SD
Age (yrs.)	28.60 ± 2.51
Height (cm)	167.40 ± 4.72
Body Mass (kg)	60.60 ± 9.99
Body Mass Index-BMI (kg m^{-2})	21.55 ± 2.62

Participants were asked to comfortably sit on the sensorized chair using arms support and backrest and perform a series of predefined postural shifts when requested from the operator. In particular the following movements were selected to be performed:

- Two consecutive forward bending of the trunk
- Lateral bending of the trunk (one left and one right)

All selected movements were performed with small, moderate and wide amplitudes, self-selected from the participants, and were also evaluated by means of video recordings. This allowed to validate the objective implemented method by comparing it to others in the literature (Bouwens et al., 2018; Mastrigt, Kamp, Veen, Vink, & Bosch, 2015).

7.2 Data processing

In Chair Movements (ICM) were calculated using two algorithms which consider respectively: the COP and EC displacements during the trial. A similar method was used only in one previous study (Fasulo, Naddeo, & Cappetti, 2019). These authors used COP displacement to calculate the number of in chair movements (ICM) and identified the number of movements only in the medio lateral direction, where a movement is detected when the difference of $x_t - x_{t-1}$ is greater than a given threshold, where x_t was the value of the x coordinate at time t.

Similarly, the method used in this work bases the ICM calculation on the displacement either of the COP or EC. The custom software allows to automatically calculate the sway parameters (starting from the time series of COP coordinates) and count the number of ICM, with the desired threshold value and sampling frequency. In this way, the COP coordinates and the sway ellipse are firstly obtained at the predetermined frequency intervals, as well as the centroid's (EC) coordinates. In particular, when either the COP or EC displacement exceeds a predefined threshold, a postural shift is detected, in a distinct way for a displacement toward a general direction (overall or general ICM), or either to AP or ML direction, as follows:

- Antero-Posterior (AP) direction

$$x_t - x_{t-1} > thresh_x$$

- Medio-Lateral (ML) direction

$$y_t - y_{t-1} > thresh_y$$

- Global ICM

$$\sqrt{(x_t - x_{t-1})^2 + (y_t - y_{t-1})^2} > \sqrt{thresh_x^2 + thresh_y^2}$$

In which x_t (or y_t) is the value of the x (or y) coordinate at time t, $thresh_x$ is equal to $thresh_y$ and t is from 0 to the end of the recording.

Five different time windows were evaluated. In particular, the data processing frequency was tested between 0.2 and 1Hz (with 0.2Hz increments), with an averaged value taken in the range from every 5 (as proposed by Fasulo et al., 2019) to 1 s. Moreover, as the purpose of this work was to define the optimal threshold and which parameter was more significant to count the number of movements, a threshold sensitivity analysis was performed in a range between 5 and 25 mm, with 5 mm increments both for COP and EC–based methods.

The choice to test another method, different from the COP one is due to the fact that the COP trajectory includes all kind of movements performed on the seat. In this way, in addition to rigid postural shifts, instantaneous movements of the COP originated by a number of other factors (such as vibrations or accelerations) would also be mistakenly recognized as an ICM. Since the ultimate goal is to clearly identify one specific movement (i.e. a rigid postural shift), removing the effect of non-postural changes, we tried to implement a method less dependent on instantaneous displacements and artifacts of the COP. That said, since the sway ellipse “averages the COP displacement, its center represents the centroid of a portion of the sway path. By tracking the EC position over time, it is ideally possible to follow the macroscopic movements of the subject's body. Microshifts, vibrations or instantaneous displacements only have the effect to move the COP around the centroid, which could be ideally considered the reference center of that particular posture.

7.3 Results and Conclusion

Data processing revealed that movement counts strongly depends on the considered processing frequency, parameters and threshold. In particular, the 0.4 Hz sampling and 5mm thresholds for EC and the 10mm for COP provided similar results when compared to the number of actual movements count obtained by means of the video recordings. In short, the method based on EC was found more able to detect ICM (an example test for one subject is reported in Fig. 7.1) and for this reason was selected as the reference algorithm. In particular, the average error) recorded on prediction of postural shifts was 5.0% with the EC method and 18.3% with the COP based algorithm. In particular, the percent error was calculated as:

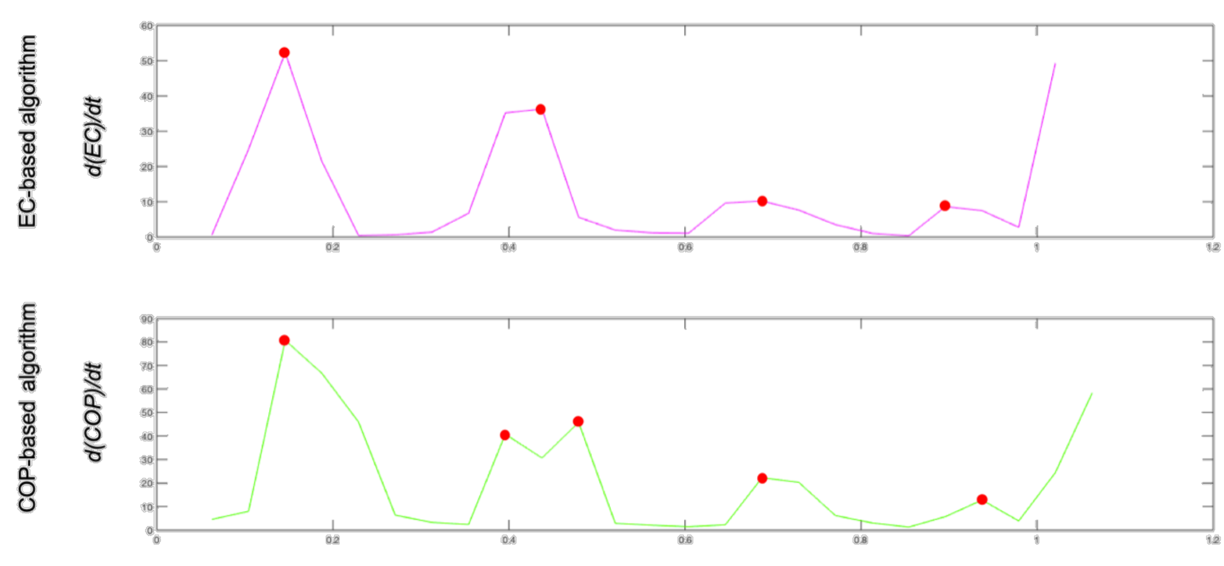

Figure 7.1: Example of the comparison between the EC (top) and the COP (bottom) based methods for one subject. EC and COP displacements are reported (purple and green lines respectively) and red dots indicate the ICM.

$$\%\ \text{error} = \left|\frac{\text{measured ICM} - \text{real ICM}}{\text{real ICM}}\right| \times 100$$

An example of the comparison between the two methods, based on one subject’s test, is shown in Fig. 7.1

The fact that the EC-based method was the most effective in determining the actual number of postural shifts is probably due to the nature of the confidence ellipse which is calculated on the basis of the COP displacement, but the latter is more sensitive to sudden perturbations and/or artifacts and vibrations. It seems then reasonable to suppose that the EC may better reflect a rigid movement of the trunk as sudden displacements of COP are mitigated in the EC.

In conclusion, based on the results of this pilot study, an ICM is considered to occur when the EC displacement, calculated across two consecutive 2.5-sec windows, exceeded the predefined threshold of 7mm. Moreover, the implemented algorithm automatically separates two ICM when they have less than 5 seconds delay. Movements occurring within the same 5 seconds window were in fact considered to be part of the same macro–movement or postural shift.

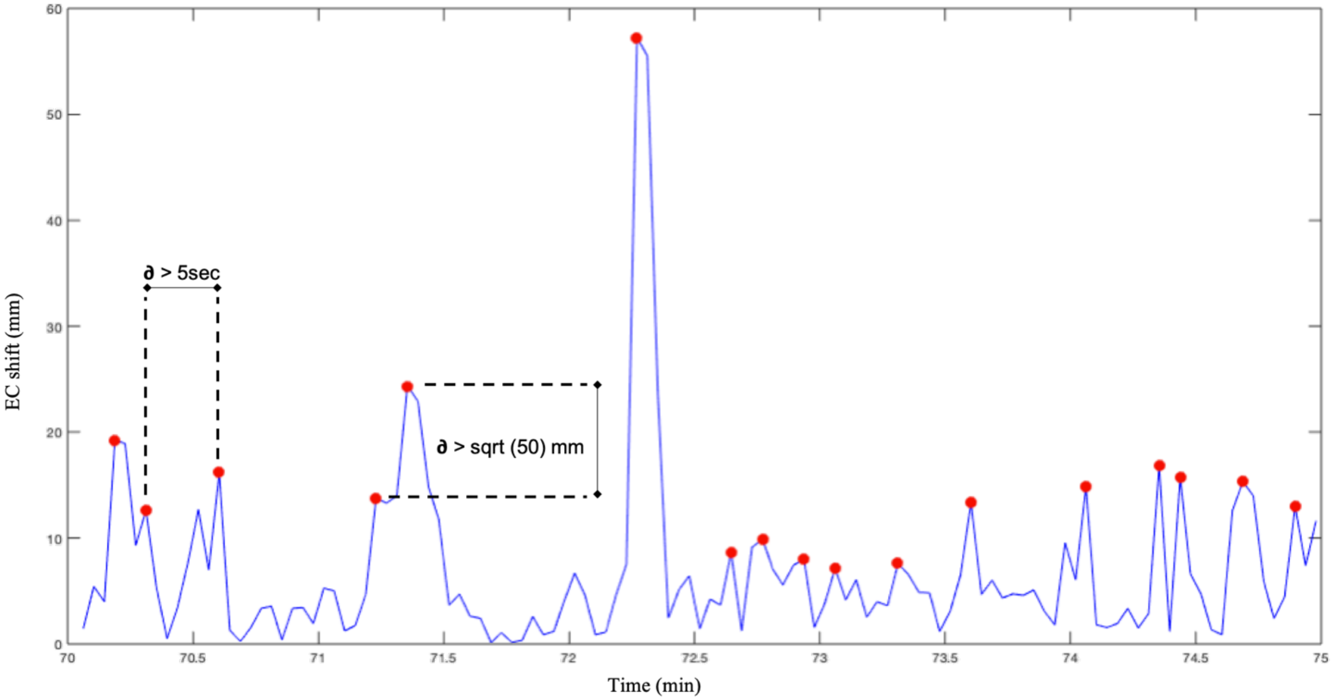

Figure 7.2: Example of the ICM calculation algorithm. The EC shift vs time is reported. Red dots correspond to detected ICM. In particular it is highlighted that at least 5 seconds occur between two consecutive ICM, and the EC shift (calculated across two consecutive windows of 2.5 seconds) must exceed sqrt(50)mm value.

A graphical representation of the algorithm principle is shown in Fig. 7.2, where the centroid's displacement over time is reported. Red dots identify the recorded ICMs; as indicated by the red arrows, an ICM is reported to occur when the difference between the EC position in the i^{th} time window and $i\text{-}1^{th}$ time window is greater than the selected threshold. The time delay between two consecutive ICM must also be greater than 5 seconds.

A such built algorithm, which considers the sway ellipse centroid calculated over relatively large time windows, whose features are not affected by sharp but sporadic changes of COP position, seem to be reliable in accurately detect rigid postural shifts both in lab and field settings, with application also to the driving context.

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Chapter 8

Postural Strategies of Bus Drivers during a regular work shift in Urban Area

Bus drivers are forced to adopt constrained postures for a long time on a daily basis. This may cause discomfort and, in the long term, represent a co-factor for the onset of musculoskeletal disorders (MSD), particularly in the low back. Objective measurements of biomechanical variables associated to sitting posture may be useful to better estimate the risk of MSD and, in recent times, in chair movements (ICM) have been shown to represent a reliable tool in characterizing sitting postural strategies. The frequency of postural shifts is, in fact, related to the perceived discomfort level, and people tend to fidget more in such a way to alleviate pressure under the buttock and thigh, in an attempt to alleviate the unpleasant sensation.

8.1 Context

As previously described in Chapter 1, several critical working tasks require that the individual adopt and maintain a sitting position for long periods of time. Among the workers forced to adopt sitting position for long times, special importance must be paid to those of the transportation sector, who work for irregular or split shifts (Anund et al., 2018). Previous studies reported that 36% of drivers who sat for more than 20 hours per week experience LBP for more than 8 days-per-year (Porter and Gyi, 2002), while this percentage drops to 16% in case of office workers who spend the same amount of time in a sitting position (Wang et al., 2011). Moreover, professional drivers are characterized by high prevalence rates of musculoskeletal problems such as LBP (Gangopadhyay and Dev, 2012; Cardoso et al., 2017) due to simultaneous exposition to prolonged sitting and vibration (Alperovitch-Najenson et al., 2010). Such environmental and task-related factors may contribute to impair driver alertness and performance, thus compromising the safety of the transport (Ting et al., 2008). In this context, the performance of postural adjustments is a recognized strategy that may alleviate the discomfort sensation (Jin et al., 2011; Le et al., 2014) which is considered as an early predictor of LBP.

In this context, the analysis of body-seat pressure has been widely used (Gyi and Porter, 1999; Kyung and Nussbaum, 2008; Porter et al., 2003) in order to predict drivers (dis)comfort state, or analyze sitting posture and related postural strategies, given the large amount of information that it can provide in spite of a minimal invasiveness and easiness of use. However, it is noticeable that in most cases, body-seat contact pressures are acquired in simulate environments and for limited amount of time (5 to 45–65 minutes). While this may be sometimes justified by the actual duration of the sitting task – Zemp et al. (2015) reported that most car trips in the United States last 20 minutes or less – in other situations the short duration of the data collection may not be sufficient. This is certainly the case of professional drivers who work for prolonged periods, also considering that it has been pointed out that at least 2 hours of testing time are required to obtain a reliable perception and assessment of comfort (Gyi and Porter, 2000).

On the basis of the above-mentioned considerations, the present study aimed to analyze the postural strategies of professional bus drivers during a real 6-hour work shift carried out on urban routes.

8.2 Methods

8.2.1 Participants

Seven male professional bus drivers (age 51.4 ± 6.6 years, stature 167.8 ± 4.4 cm, body mass 78.8 ± 15.4 kg, working experience in the transportation sector 20.8 ± 5.8 years) employed by the public transport company ASPO S.p.A. (Olbia, Italy) were recruited for this study on a voluntary basis (Tab. 8.1). All participants provided written informed consent, after a detailed explanation of the purposes of the study and a description of the experimental methodology.

Table 8.1:Anthropometric and experience features of the participants. Values are expressed as mean ± SD

Participants #	7
Age (years)	51.4 ± 6.6
Height (cm)	167.8 ± 4.4
Body Mass (kg)	78.8 ± 15.1
Years of Experience	20.8 ± 5.8

The study was conducted in accordance with the ethical standards of the institutional research committee and with the 1964 Helsinki declaration and its later amendments and all participants signed an informed consent agreeing to participate.

8.2.2 Experimental procedure

Each test session included an actual 6-hours work shift performed across the urban routes scheduled for a regular working day by the company. Participants were asked to drive maintaining a posture as natural as possible, while contact pressure at the body-seat interface was continuously acquired during the entire period (Fig 8.1) by means of pressure sensitive mats previously described in chapters 6 and 7. As scheduled, all drivers were allowed to have 10-minute rest breaks at the bus terminal approximately every 50 minutes of continuous driving. This resulted in 6 breaks during the entire shift. Participants were also required to provide subjective discomfort ratings verbally every 90 min using the two-part questionnaire developed by Sammonds et al. (2017) and previously described in Chapter 6.

8.2.3 Interface Pressure Data Acquisition and Post-processing

Data on the contact pressure at the body-seat interface were obtained by means of the Tekscan 5330E pressure-sensitive mat at 10 Hz sampling frequency.

Data associated with sit and stand up phases, as well as seat and backrest adjustment were discarded as not relevant for the analysis.

Starting from raw pressure data, sway path and sway area were calculated (Era and Heikkinen, 1985) and the number of ICMs was obtained on the basis of the sway ellipse’s centroid displacement, as described in Chapter7, by means of the dedicated custom software developed under the Matlab® (The MathWorks, Inc, Natick, MA, USA) environment.

Figure 8.1: Photo of the pressure sensitive mats positioned on the seat (left). Bus driver during a driving session (right).

8.2.4 Statistical Analysis

*Whole trial analysis***.** For the analysis of the data relating to the entire duration of the trial, it was considered as a continuous task, excluding the data associated to the breaks and considering only the continuous driving periods. The existence of possible differences in ICMs performed each 5 minutes as well as in sway parameters was assessed by using the one-way analysis of variance for repeated measures (ANOVA-RM), by means of the IBM SPSS Statistics v.20 software (IBM, Armonk, NY, USA). The independent variable was the time and the dependent variable the number of ICMs and sway parameters in turn (area, path, and EC coordinates). The significance level was set at p=0.05. Multiple comparison tests vs. baseline value of parameters values (those relative to the first 5-min interval) were performed. Pearson product moment correlation test was performed in order to detect any particular correlation between time and selected variables during the whole trial, at 5-min intervals.

Finally, in order to analyze the relationship between the obtained variables and subjective discomfort ratings, their amounts every 90 minutes were considered, with the same frequency with which data relating to subjective discomfort were collected. Pearson correlation analysis was then performed to assess the existence of particular relationship between data, setting the level of significance at p=0.05.

Chunk analysis. In this case the existence of possible differences in parameters value was assessed using the one-way analysis of variance for repeated measures (ANOVA RM), always performed using the IBM SPSS Statistics v.20 software (IBM, Armonk, NY, USA). The independent variable was the time and the dependent variable the number of ICM and sway parameters. The significance level was set at p=0.05. Multiple comparison tests vs. baseline values (relative to the first 5-min interval) were also performed. Finally, the relationship between the number of ICM and sway each 5 minutes during the chunk vs time was assessed by calculating the Pearson product moment correlation index. Even in this case the level of significance was set at p=0.05.

8.3 Results

Whole trial analysis. Considering the whole trial duration, RM-ANOVA did not detect any main effect of time on number of ICM and sway parameters. Pearson correlation test found a positive significant small correlation between time and overall number of ICM ($r = .310$, $p < .05$), sway path ($r = .333$, $p < .01$), AP and ML EC coordinates ($r = .378$, $p < .01$ and $r = .254$, $p < .05$) (Fig. 8.2).

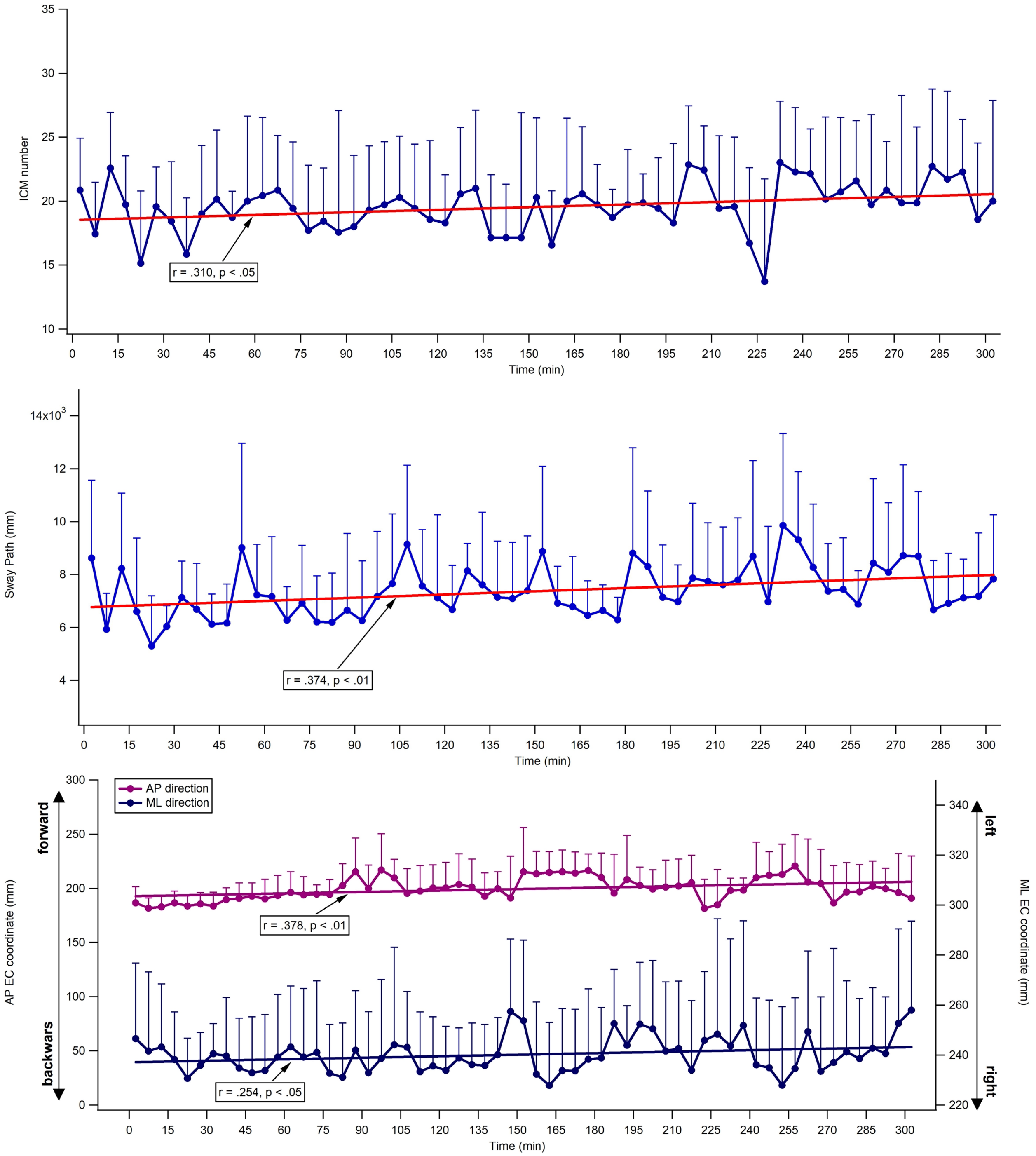

Figure 8.2: Top) Number ICM, middle) sway path and bottom) AP and ML coordinates during the whole trial

A significant positive moderate correlation was also found between time and overall discomfort ratings (r = .597, p < .05) (Fig. 8.3), time and number of ICM performed each 90 minutes (r = .896, p < .05) and perceived discomfort vs. number of ICM performed (r = .429, p < .05). No effect of time has been highlighted on the values of the discomfort indices relating to body parts, while significant correlations were founded between overall discomfort and: upper back (r = .619, p < .001), lumbar region (r = .651, p < .001), sitting bones (r = .622, p < .001) and edge of the seat contact (r = .733, p < .001). High, even no significant, correlations were reported between discomfort and sway parameters (Tab. 8.2)

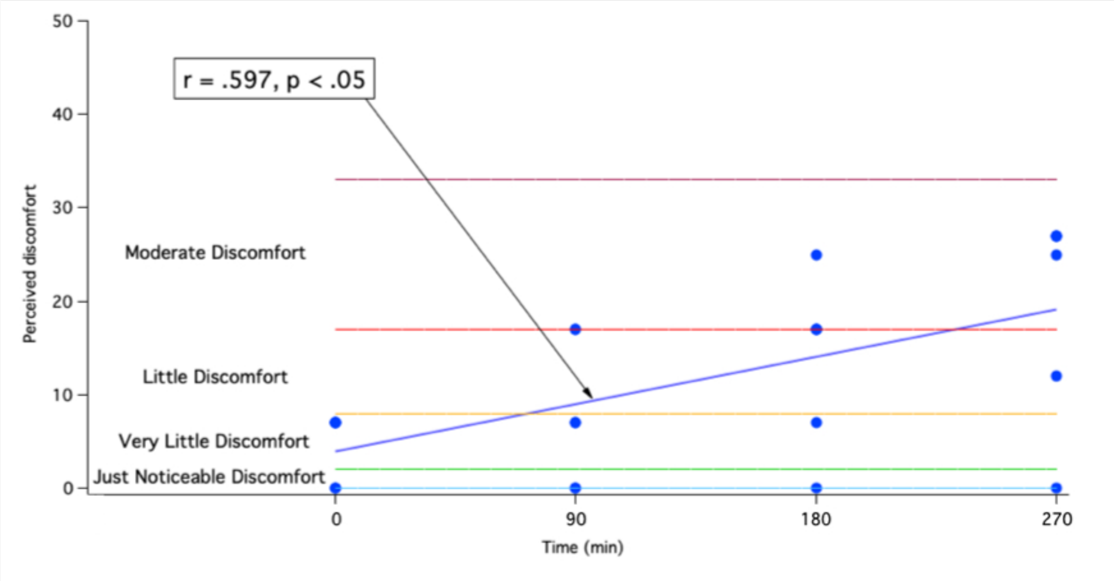

Figure 8.3: Trend of overall discomfort during the whole shift. Blue dots represent subjective ratings. Attention must be given when interpreting these graphs. Some dots are overlapped when subjects gave the same rating.

Chunk analysis. When the task chunks were analyzed separately, RM-ANOVA did not detect any significant effect of time on ICM (Fig. 8.4). Significant effect of time was detected for sway area [F (9,399)= 14.123, p < .001], sway path [F (9,399)= 16.076, p < .001], EC velocity [F (9,399)= 4.130, p < .01] and ML EC coordinate [F (9,399)= 4.959, p < .01].

Table 8.2: Pearson correlation of perceived discomfort vs sway parameters

	Upper Back	*Lower Back*	*Sitting Bones*	*Buttock Area*	*Edge of Seat*	*Overall*
Sway Path	.952	.995	.978	.741	.558	.943
Sway Area	.887	.965	.990	.843	.689	.985
EC velocity	.594	.751	.917	.994	.937	.960
AP EC $_{coordinate}$	.157	.363	.630	.934	.992	.724
ML EC $_{coordinate}$	.951	.995	.978	.743	.560	.994

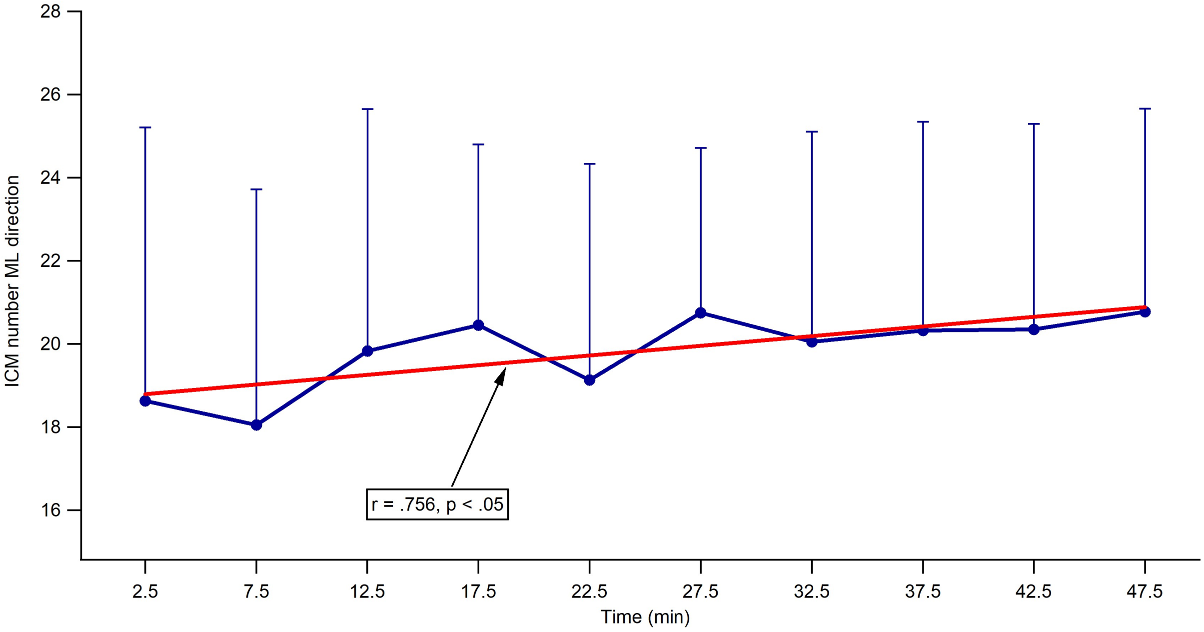

Figure 8.4: ICM number during a chunk lasting 50 minutes

The Pearson correlation test showed the existence of significant moderate-to-large correlation (Cohen, 1988) for time vs ICM in ML direction (r = .756, p < .05), while no significant correlation was reported for AP and overall ICM (r = .481 and r = .431 respectively). Regarding the sway parameters, significant large negative correlations were evidenced between time and sway path (r = -.770, p <.01), sway area (r = -.813, p <.01), EC velocity (r = -.653, p <.01). EC was also found to significantlu shift on the right side of the seat during the chunk (r = .929, p <.01) (Fig. 8.5).

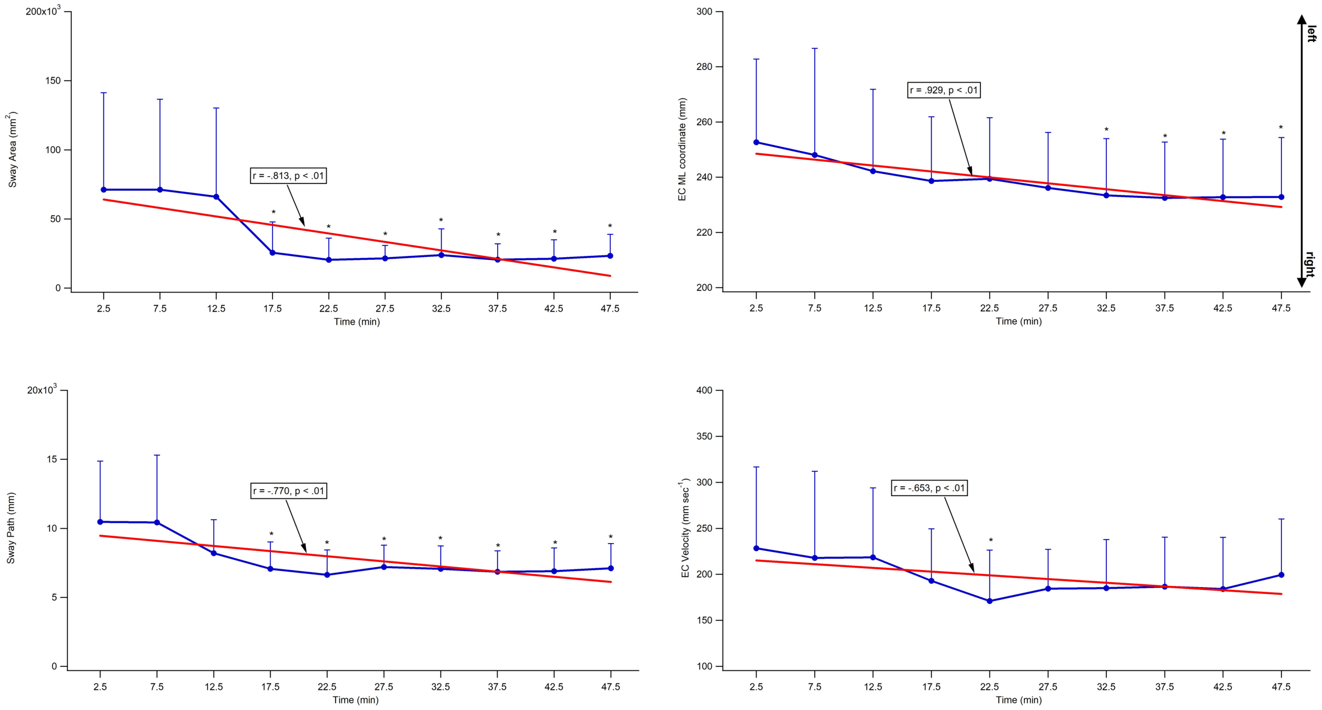

Figure 8.5: Sway parameters trend during the homogeneous chunk

8.4 Discussion

This study aimed to quantitatively evaluate postural strategies and discomfort of bus drivers during a real long-term work-shift, using ICM as calculated from body-seat interface pressure data. To this aim, we considered the number of postural shifts defined on the basis of the position of the center of the sway ellipse, while in most previous studies ICMs were rather calculated from changes in body-seat contact pressure values (Na et al., 2005; Le et al., 2014). The choice to consider the displacement of the confidence ellipse's center was mainly due to the fact that there are circumstances in which a pressure change does not necessarily reflect a macro-movement of the body over the seat, as it happens when a sudden random vibration (for example originated by road asperities) occurs. Moreover, being the sway ellipse calculated over a 2.5s time windows, its features are not affected by sharp but sporadic changes of COP position.

Our initial hypothesis was that, as the shift progresses, drivers unconsciously perform more postural adjustments (i.e. the number of ICMs increase), in order to alleviate the pressure in the buttock region as previously reported for the case of office workers and quay crane operators (Bendix et al., 1985; Fenety et al., 2000; Grandjean et al., 1960; Jurgens et al., 1989; Michel et al., 1994; Rieck et al., 1969; Na et al., 2005; Le et al., 2014; Mansfield, 2017; Vink 2017; Sammonds et al., 2017; Leban et al., 2019). In particular Sammonds et al. (2017) justify this behavior, by stating that when workers first sit they feel little discomfort and move little while, over extended periods of sitting, discomfort increases, thus leading to significant increases in ICMs. Moreover, we expected to observe an increase on sway parameters in time, due to the fact that, as previously reported also in Chapter 4, during prolonged sitting posture, trunk sway tends to increase with time, suggesting the onset of fatigue factors (Hendershot et al., 2013; van Dieen et al., 2012; Leban et al., 2017).

The obtained results considering the whole shift, partly confirm this hypothesis. In fact, it was observed a significant correlation between both perceived discomfort and number of ICM and time, even if the increase in discomfort was lower than expected. This result could depend on the fact the drivers, alternating driving periods with rest breaks, may thus have alleviated the level of fatigue, as previous studies reported that interrupting prolonged sitting with breaks may be an effective fatigue countermeasure (Wennberg et al., 2016). In addition, our hypothesis of an increase in trunk sway was also confirmed; in particular, sway path and area were found to increase with time with a strong, but moderate, correlation.

A more in-depth analysis, which took into account only homogeneous part of the shift during which the driver cannot leave the cockpit (i.e. chunks), shows that the number of ICM significantly increases only in the ML direction, while sway path and area show a marked decreasing trend over time. This suggests that, as time progresses, drivers tend to perform a higher number of postural shifts (especially in the ML direction) but with progressively smaller amplitudes if compared to the first part of the chunk. This phenomenon needs to be analyzed under two different aspects. Firstly, ICM results are in agreement with previous studies, which report an increase of ICM number during the working task (Na et al., 2005; Le et al., 2014; Mansfield, 2017; Vink 2017; Sammonds et al., 2017; Leban et al., 2019). Secondly, the decrease in sway parameters during the homogeneous chunk is somehow in contrast with our initial hypothesis. Previous authors reported, as said, an increase of trunk sway with time, suggesting that fatigue plays an important role in modifying trunk stability while sitting (Hendershot et al., 2013; van Dieen et al., 2012; Leban et al., 2017). However, it should be noted that, except Leban et al. (2017), other authors did not investigate working tasks; moreover no one of previous studies was performed in the field. It is possible that the presence of quite frequent breaks scheduled by the transport company, during which the worker is allowed to almost fully recover its initial state of well-being, changes the trunk sway trend in the subsequent chunk. Finally, the fact that ICM increase mostly in the ML direction may indicate the attempt to relieve the pressure on the buttocks, shifting alternating loads between the right and left sides of the chair.

In practice, it is likely that drivers tend to perform less but wider postural movements or adjustments at the beginning of the chunk in an attempt to find the best driving position and, once the correct one is found, they make a greater number of small adjustments until the next break. This process is then repeated during the whole shift. Nevertheless, our data also suggest that, as the driving shift progresses, they perform progressively wider postural adjustments in order to find the optimal position. This behavior is also coupled to a tendency to orient the posture toward the right side of the pan. Such tendency is probably maybe caused by the need to deal with the accelerator and brake pedals: after some time spent driving, drivers adapt their posture to better interact with controls, thus adopting a less neutral posture with respect to the first driving bout. As seen in Chapter 3, non-neutral postures can lead to biomechanical overload and musculoskeletal problems. Despite this, it seems that, considering the whole shift, drivers shift overall their posture progressively to the left, maybe trying to compensate the load shift on the right side during the homogeneous chunks or driving bouts. It is likely that they sit more leftward at the beginning of each chunk, unconsciously anticipating their tendency to shift to the right side during the continuous driving bout.

On the other hand, it is quite evident a trend of increase for overall driver’s discomfort (Fig. 3), which seems to be more related to ICM than trunk sway. An increase in discomfort might indicate that, despite the breaks, a residual level of discomfort still remains, probably due to accumulation of physical and mental fatigue, as testified also by the increase in sway when considering the whole shift.

However, when the single body regions were analyzed, no significant increase of local discomfort was found. This is probably due to the fact that, as said in Chapter 3, participants were not able to locate a specific part of their body in which discomfort was most preeminent as they were highly concentrated on driving task.

Some limitations of the study should be acknowledged. Firstly, being this a study to assess the feasibility of monitoring the body-seat interface pressure during a real long-term driving work shift, the size of the tested sample was limited. Secondly, the effect of anthropometric characteristics was not taken into account, though it is known that stature, for example, affects neck, shoulder, buttock and thigh comfort. Stature may thus influence posture, and differences in body positioning on the seat may be seen when taking into account anthropometric features (Na et al., 2005; Kyung et al., 2008). Finally, the effect of vibrations was not taken into account, and it is known that this aspect could also lead to an augmented discomfort.

8.5 Conclusion

The results of the present study demonstrated the feasibility of application of a technique based on the use of pressure sensitive mats to investigate the postural adjustment of professional drivers under real conditions and for long-term monitoring. By exploiting the properties of several COP-based measurements, it was possible to have available a set of markers (the number of ICM and trunk sway parameters) which represent a promising tool, useful to characterize the changes in posture and sitting behavior consequent to discomfort and fatigue.

Further studies on larger cohorts are necessary to clarify whether the results here obtained are generalizable to all categories of drivers operating in urban area. Also, it would be interesting to verify if other kind of drivers, for instance those who work on long-distance routes, exhibit similar or different behavior.

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Chapter 9

Trunk sway changes in professional bus drivers during actual shifts on long-distance routes

9.1. Introduction

Professional bus drivers are required to efficiently and safely perform their task continuously for long periods of time (up to 10 hours per day after 8 consecutive hours off duty, according to the Federal Motor Carrier Safety Administration, USA) respecting tight schedules while maintaining a fixed sitting position. In comparison with other kind of professional drivers, bus drivers operate on longer distances for a prolonged time (Lee et al., 2019) with little or no control over their working environment (Tse et al., 2006) in terms of cockpit ergonomics (a fact which may lead to ergonomic mismatch, Yasobant et al., 2015), passengers behavior (European Agency for Safety and Health at Work, 2011; Teixeira and Fischer, 2008) and traffic conditions (Querido et al., 2012). Thus, it is not surprising to note that professional driving has been largely identified as one of the most stressful occupations (Evans et al., 1999). Such task is physically challenging, especially because drivers are forced to adopt prolonged non-neutral postures, requiring constant activity of the muscles involved in the neck support, the stabilization of the trunk and the movement of upper and lower limbs (Winkel and Westgaard, 1992; Kruizinga et al., 1998). In addition, bus drivers may experience psychological stressors like depression, anxiety and post-traumatic stress disorder due to negative passenger interaction (Evans et al., 1994; Ahlstrom et al., 2018). The adoption of prolonged constrained posture is originated by the task requirement, which involve a continuous control over steering wheel and pedals while keeping a constant attention at the road environment (Van Veen and Vink, 2016). Moreover, it should be considered that the driver’s feet do not generally perform any body support action as they are mostly engaged in the control of pedals (Andreoni et al., 2002). Such constriction represent an important negative factor for comfort (Grieco,1986; Andreoni et al., 2002) as the sustained submaximal contractions of back and trunk muscles maintained for long periods may induce a high level of discomfort and neuromuscular fatigue (Hosea et al., 1986; Jorgensen et al., 1988; El Falou et al., 2003; Baucher and Leborgne, 2006). In particular, muscle fatigue while driving (which has been studied by examining changes in muscular tension in shoulder and neck muscles, Sheridan et al., 1991; Wikström, 1993; Balasubramanian and Adalarasu, 2007; Hirao et al., 2007) acutely impairs driver alertness and disrupts cognitive performance, leading to an overall decrease in safety of the transportation (Leinonen et al., 2005; Ting et al., 2008).

In such a context, there is the need for methods to assess drivers' workload, inattention, comfort and fatigue by adopting multi-method approaches in order to early detect any information that can be useful to estimate the existence of potential risky conditions (Lohani et al., 2019). This may allow for discomfort and/or fatigue indirect measurements to be made remotely, in a less invasive way of subjective discomfort ratings (Sammonds et al., 2017). To this purpose, as discussed in previous chapters, several authors recently focused their research on prolonged sitting and its relationship with discomfort states using a variety of tools like video analysis (Womersley and May, 2006), accelerometers (Ryan et al., 2011), optoelectronic systems (Dunk and Callaghan, 2005), force sensors (Yamada et al., 2009; Zemp et al., 2016b) and pressure distribution sensors (Zemp et al., 2016a). Among them, pressure-sensitive mats represent a very appealing solution due to their easiness of setup and use (Bontrup et al., 2019), and their limited influence on the execution of the task (Zemp et al., 2016a; Kamiya et al., 2008). Moreover, seat-body contact pressure may represent a very effective tool in assessing discomfort onset as this variable has been shown to be associated with subjective perception of drivers (de Looze et al., 2003; Dunk and Callaghan, 2005; Kolich et al., 2004).

A possible way to characterize the effects of prolonged sitting posture on the basis of body-seat contact pressure, involves the analysis of postural shifts (ICM) and trunk sway through processing of the center-of-pressure (COP, namely the point of application of the resultant of the forces exchanged by body and seat) time series, focusing the attention on the sole stability of trunk (Vette et al., 2009; Serra-Ano al., 2015; Leban et al., 2017). As deeply analyzed in previous chapters, ICM have been identified to be related to discomfort state (Na et al., 2005; Le et al., 2014), and an increase over time would reflect an increase in perceived discomfort. This leads, in fact, to change posture more frequently, in order to reduce the unpleasant sensation and alleviate pressure under the buttock and thigh region. Postural sway has instead been largely investigated in the case of upright standing, and its features have been found extremely useful in research and clinical contexts to characterize the performance of the postural control system (Visser et al., 2008). Similarly to what observed for standing, trunk stability has been demonstrated to be influenced by sensorimotor impairments caused, for example, by neurologic conditions such as brain and spinal cord injuries (Genthon et al., 2007; Perlmutter et al., 2010; Milosevic et al., 2015) and musculoskeletal disorders like low back pain (Radebold et al., 2001). Interestingly, it has been recently reported that, during prolonged sitting posture, trunk sway tends to increase with time, and this suggest its possible use as biomarker for fatigue (Hendershot et al., 2013; van Dieen et al., 2012; Leban et al., 2017). Nevertheless, to these author’s knowledge, few studies have investigated this issue under actual working conditions and very few investigated effects of prolonged actual driving, probably due to the difficulties and challenges associated with analyzing such a task in real-world with respect to the use of simulated environment.

On the basis of the above considerations, the aim of this study is to characterize in chair movements, trunk sway and their relationship with discomfort, in a cohort of professional experienced bus drivers during actual long-term shifts carried out on extra-urban routes. The hypothesis to test is that ICM and trunk sway increase during the shift, thus representing the effect of cumulative discomfort and neuromuscular fatigue respectively.

9.2. Methods

9.2.1 Participants

Fourteen male experienced professional bus drivers currently employed at the largest public transport regional company of Sardinia (ARST S.p.A. Cagliari, Italy) were recruited for this study on a voluntary basis. At the time of the experimental trials, they were free from any musculoskeletal disorder for at least 12 months according to their medical records and self-report. All participants provided written informed consent after a detailed explanation of the purpose and experimental methodologies of this study, which was conducted in accordance with the ethical standards of the institutional research committee and with the 1964 Helsinki declaration and its later amendments. Their main demographic and anthropometric features are reported in Tab. 9.1.

Table 9.3: Anthropometric and demographic features of the participants. Values are expressed as mean ± SD

	Mean ± SD
Age (yrs.)	45.79 ± 6.16
Height (cm)	172.08 ± 6.17
Body Mass (kg)	79.50 ± 9.95
Body Mass Index (kg m^{-2})	26.95 ± 4.08
Experience (yrs.)	17.42 ± 5.82

9.2.2 Experimental procedure

Drivers were tested in the period October-November 2018 during actual 6 to 8-hour-long shifts which included service on regional routes as scheduled by the company. Trials were performed on a Scania Irizar i4 bus mounting an air-suspension seat in the cockpit. All shifts started either in the early morning or afternoon. Thus, in most cases, part of the task was performed under dawn or twilight conditions. Overall, 72.5 hours of service were monitored.

Before the beginning of the shift, participants adjusted the bus seat at their convenience. Then, they were asked to drive while maintaining their usual working posture (Fig. 9.2). As per company policy, drivers were allowed to rest after approximately 120 minutes of continuous driving, taking breaks of variable duration (but not exceeding 45 minutes in any case) at the bus terminal. They were also required to provide information about perceived discomfort every 60 minutes using the 2-part survey proposed by Sammonds et al. (2017) better described in Chapter 6.

Figure 9.1: Photo of the pressure sensitive mats positioned on the seat and connected to the computer.

Contact pressure data at the body-seat interface was continuously collected by mean of a pressure-sensitive mat (Tekscan 5330E 471.4 x 471.4 mm active area, 1024 sensing elements arranged in a 32 x 32 matrix) previously employed in similar studies (Andreoni et al., 2002; Pau et al., 2016; Leban et al., 2018) at 10 Hz sampling frequency. The sensor was connected to a two-port hub (Tekscan Versatek) and then to a PC via USB connection as shown in Fig. 9.1. Before each trial, the mat was calibrated as described in Chapter 6.

Figure 9.2: Bus driver during a driving session.

9.2.3 Data processing

Task-induced trunk sway was assessed on the basis of COP time-series acquired by the Tekscan system. Figure 9.2 shows a test session, with a driver driving during the trial. Raw data were exported as text files using the management software provided by the manufacturer (Tekscan Conformat Research v.7.20) and post-processed using a dedicated custom software developed under the Matlab® environment (MathWorks, Inc, Natick, MA, USA). On the basis of the raw COP trajectory data (Fig. 9.3), as described in chapters 6 and 7, the trunk sway parameters and ICM data were calculated:

All data were averaged over 15-min blocks. This choice was made following the instructions of previous similar researches (Fenety et al., 2000). Data related to the first 5 minutes of each trial as well as those of the first 5 minutes after any scheduled break, were discarded to remove any possible artifact originated by the sitting and seat-adjustment phases. Number of ICM was also calculated via the Matlab software, using the same settings reported in Chapter 7.

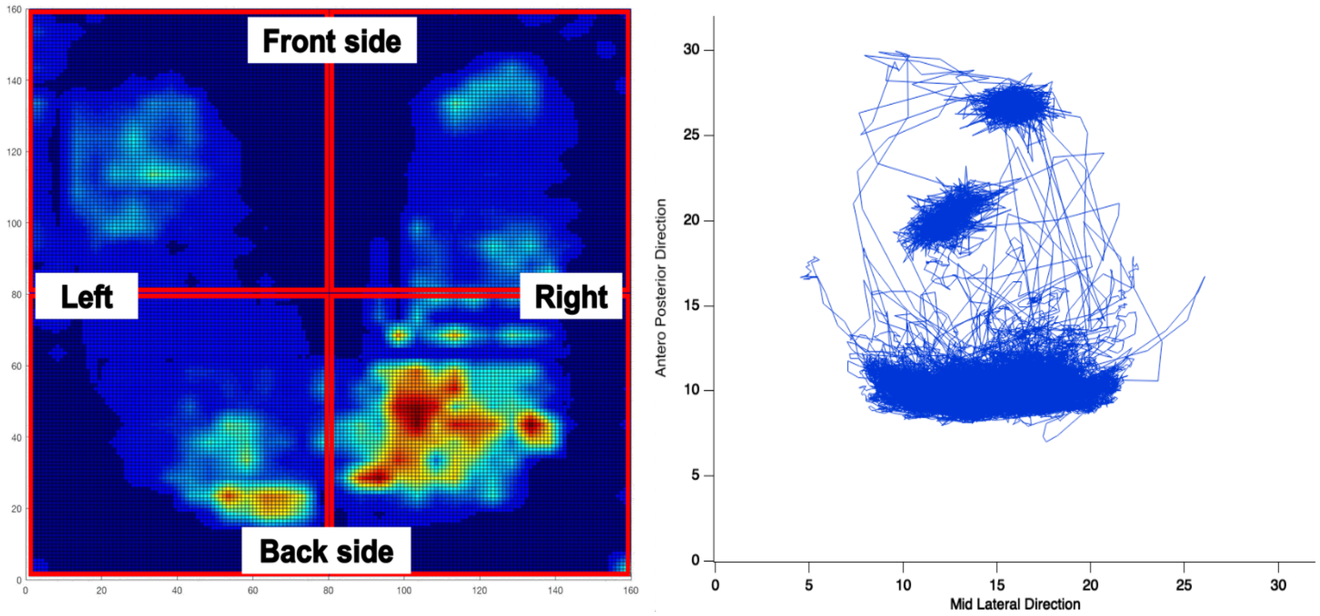

Figure 9.3:On the left an example of pressure distribution in the seatpan: left and right, front and back sides are identified with the four quadrants. On the right an examople of the EC path during the entire trial.

9.2.4 Statistical analysis

The existence of changes in ICM and trunk sway parameters induced by the work-shift was assessed by means of one-way analysis of variance for repeated measures (ANOVA-RM), setting time as independent variable and the previously listed sway parameters and ICM as dependent variables. The significance level was set at p = 0.05. Multiple comparison tests vs. baseline value (the value referred to the first 15-min interval) were performed using the Bonferroni method. Data were preliminarily checked for normality (using the Shapiro–Wilk test), homogeneity of variances (Levene's test) and presence of outliers. Pearson product moment correlation analysis was also performed to assess the relationship between ICM, each of the sway parameter and the shift time. Even in this case the level of significance was set at p = 0.05. Qualitative trend across time of the perceived discomfort ratings were evaluated.

9.3. Results

9.3.1 Sway parameters

The trends of the sway parameters during the work shift are reported in Figure 9.4. The statistical analysis detected a significant effect of time on sway area [F(7,159) = 2.86, p = 0.008], EC velocity in AP direction [F(7,159) = 2.15, p = 0.043] and COP maximum displacement in ML direction ([F(7,159) = 3.46, p = 0.002], while no effect was found for sway path [F(7,159) = 2.08, p = 0.050], EC overall velocity [F(7,159) = 1.67, p = 0.122] and ML direction [F(7,159) = 1.42, p = 0.202], COP maximum displacement in AP direction [F(7,159) = 1.84, p = 0.084] and EC coordinates in both AP [F(7,159) = 1.24, p = 0.287] and ML [F(7,159) = 0.90, p = 0.506] directions.

The results of the correlation analysis (reported in Tab. 9.2) show that all sway parameters were positively correlated with time. In particular, strong associations were observed for sway area, sway path, EC velocity and COP displacements in AP and ML directions (r in the range 0.81-0.93). EC coordinates were found positively correlated with time only in AP direction (r= 0.81). An example of changes in sway features with increasing time is shown in Fig. 9.4.

Table 9.4: Pearson product moment correlation coefficient between time shift and sway parameters (†p < 0.05, ‡p < 0.01.)

	Parameter	*r*
Time vs.	*Sway Area*	*0.864*‡
	Sway Path	*0.727*†
	COP displacement in AP direction	*0.930*‡
	COP displacement in ML direction	*0.892*‡
	EC velocity	*0.844*‡
	EC AP velocity	*0.823*†
	EC ML velocity	*0.772*†
	EC coordinate in AP direction	*0.807*†
	EC coordinate in ML direction	*0.657*

9.3.2 In Chair Movements

ICM trend over time is reported in Figure 9.5. In particular, statistical analysis detected a significant effect of time ICM performed in AP direction [F(7,159) = 3.54, p = 0.002], while no effect was found for overall and ML ICM [F(7,159) = 1.89, p = 0.077 and F(7,159) = 1.45, p =

0.189 respectively]. On the other hand, correlation analysis highlighted strong large positive correlations for all considered ICM with time (r = .912, p <.01, r = .799, p <.05, r = .861, p <.01 respectively for AP, ML and overall ICM).

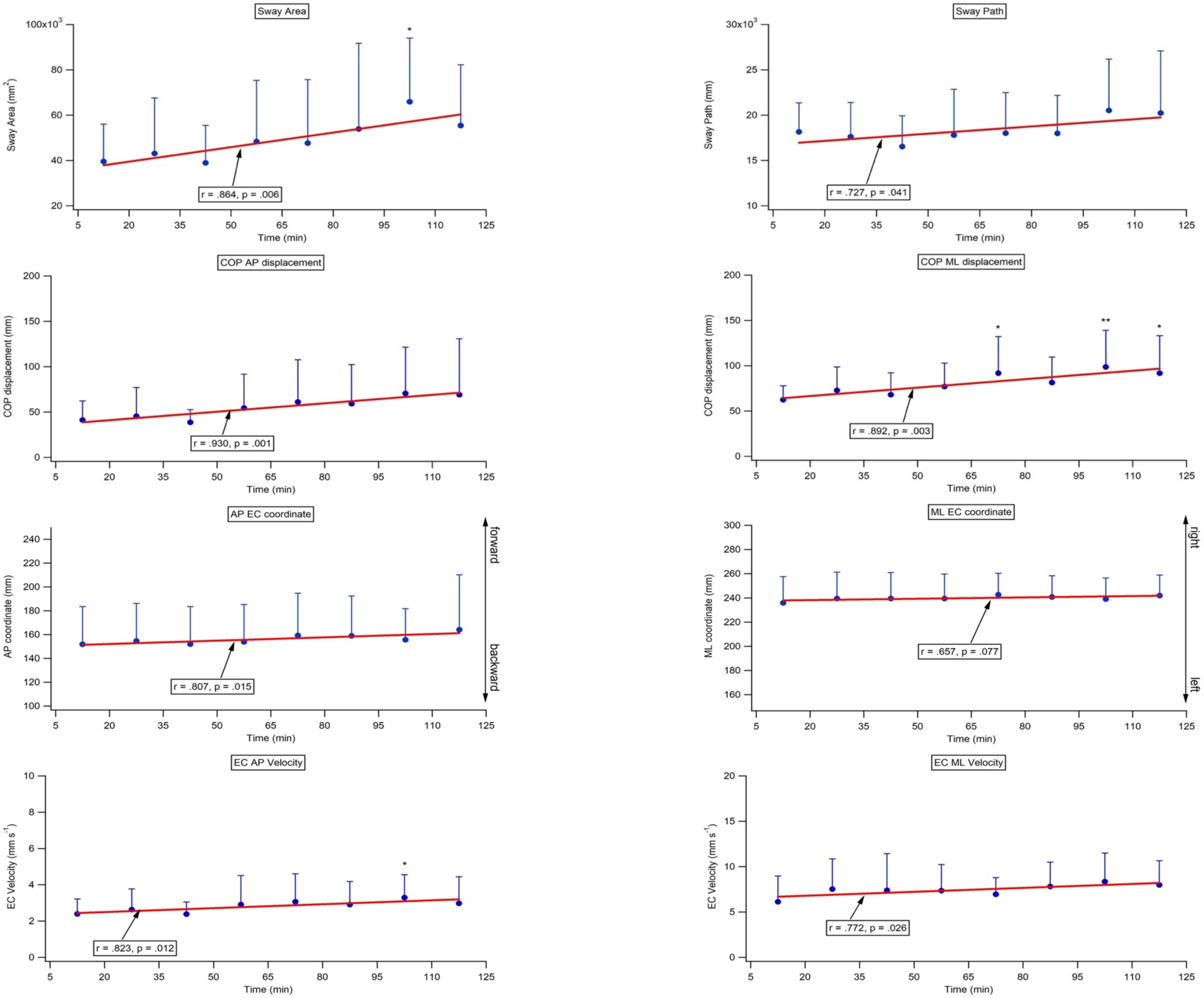

*Figure 9.4: Trends of outcome variables over time. Error bars indicate standard deviations, the symbols * and ** indicates a significant difference vs. baseline value ($p < 0.05$ and $p < 0.01$ respectively).*

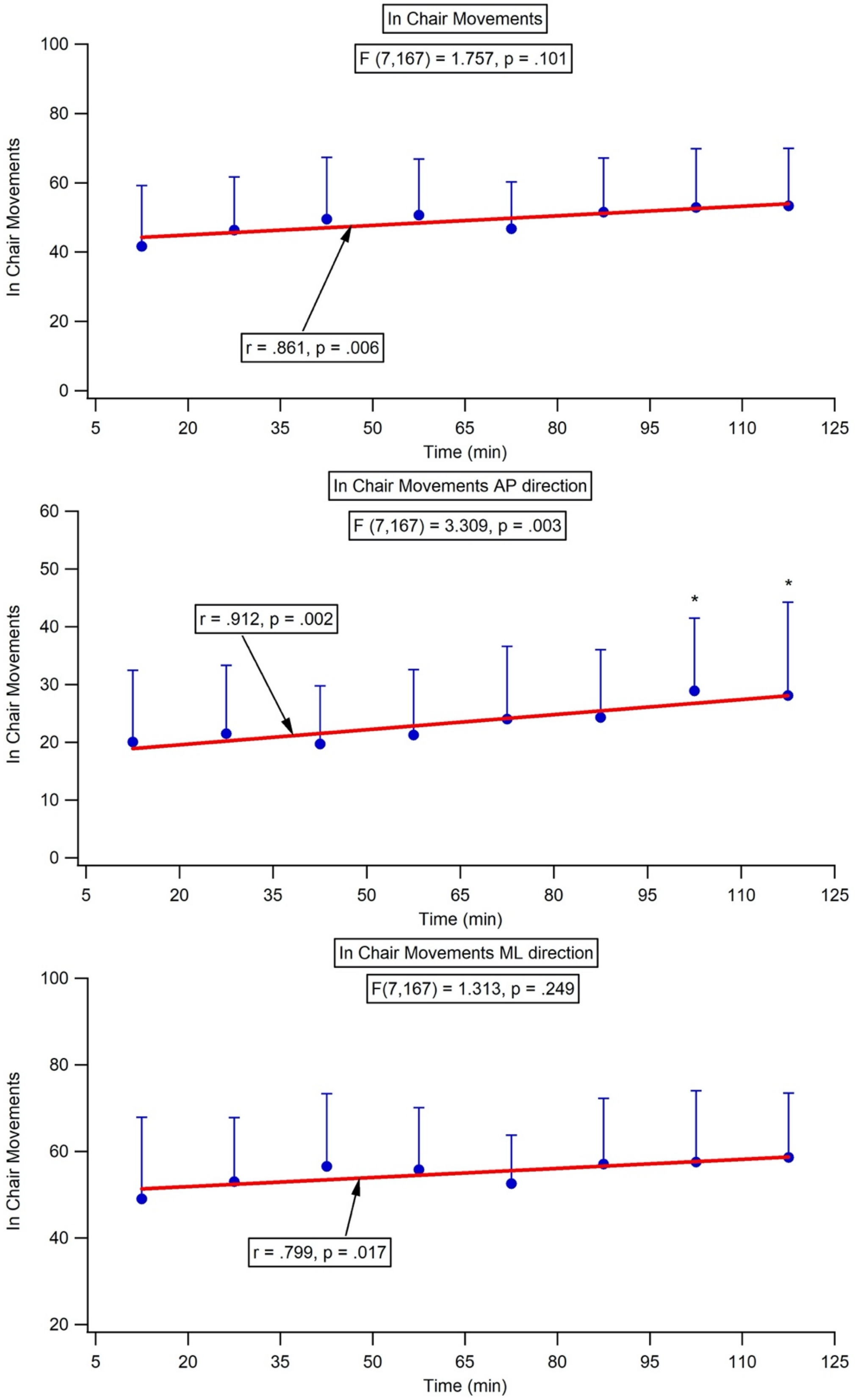

Figure 9.5: ICM trend over time.

9.3.3 Perceived discomfort

Overall perceived discomfort ratings trend over time is shown in Fig. 9.6. Curve slopes for body regions and overall discomfort are reported in Tab. 9.3.

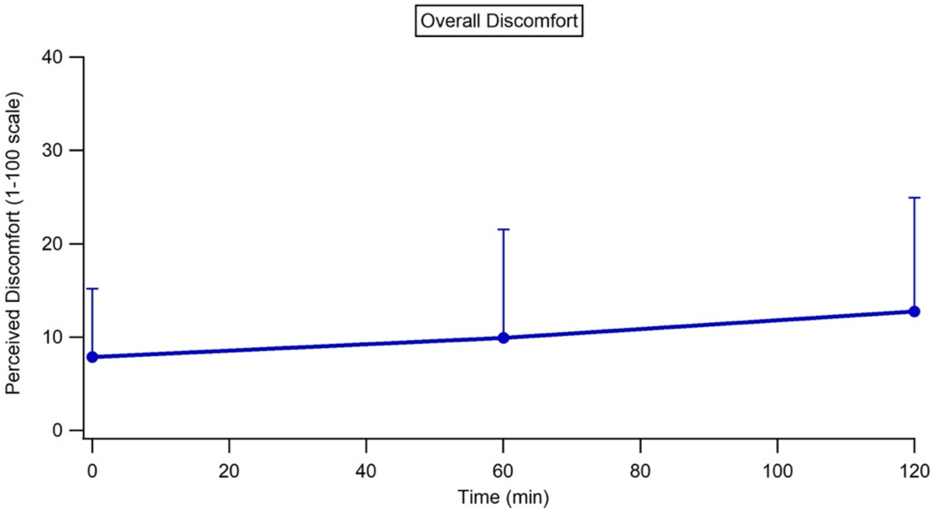

Figure 9.6: Trend of overall perceived discomfort over time. Error bars indicate standard deviations.

Table 9.5: Slope of Perceived Discomfort rating curves over time

	Perceived Discomfort	*r*
Time vs.	*Upper Back*	*0.998*
	Lower Back	*0.866*
	Buttock Area	*0.974*
	Sitting Bones	*0.998*
	Edge of Seat Contact	*0.999*
	Overall	*0.996*

9.4 Discussion

The purpose of the present study was to perform a long-term monitoring of trunk sway induced by the driving task along with in a cohort of professional bus drivers who perform their task on extra-urban routes. In particular, we aimed to detect the onset in modifications of sitting postures and sway parameters associated with work shift progression, discomfort and/or fatigue in order to provide information on driver's state potentially useful for the development of remote monitoring tools. Generally speaking, our data reveal an increasing trend for perceived discomfort, number of ICM and trunk sway parameters as driving time progresses, with significant changes in trunk movements occurring at different times from the beginning of the shift depending on the considered parameter. In particular, sway velocity in AP direction and sway area (an example of the difference in sway area for one subject is reported in Fig. 9.7) were found to be significantly higher, with respect to the baseline values, after approximately 100 min of continuous driving. Similarly, ICM in AP direction were significantly higher after about 100 min from the beginning of the shift. Maximum COP displacements were found to increase with time: in particular in ML direction significant differences with respect to the baseline were reported after approximately 70 min from the beginning of the driving task. EC coordinate significantly moved forward as the shift progressed.

Although, to the authors' knowledge, to date no data are available on postural sway and ICM in real long distance driving, our findings appear to be consistent with those reported in several previous studies performed on workers who adopted long-term sitting postures, other than drivers, like office workers and quay crane operators (Bendix et al., 1985; Jensen and Bendix, 1992; Fenety et al., 2000; Na et al., 2005; van Dieen et al., 2012; Hendershot et al., 2013; Le et

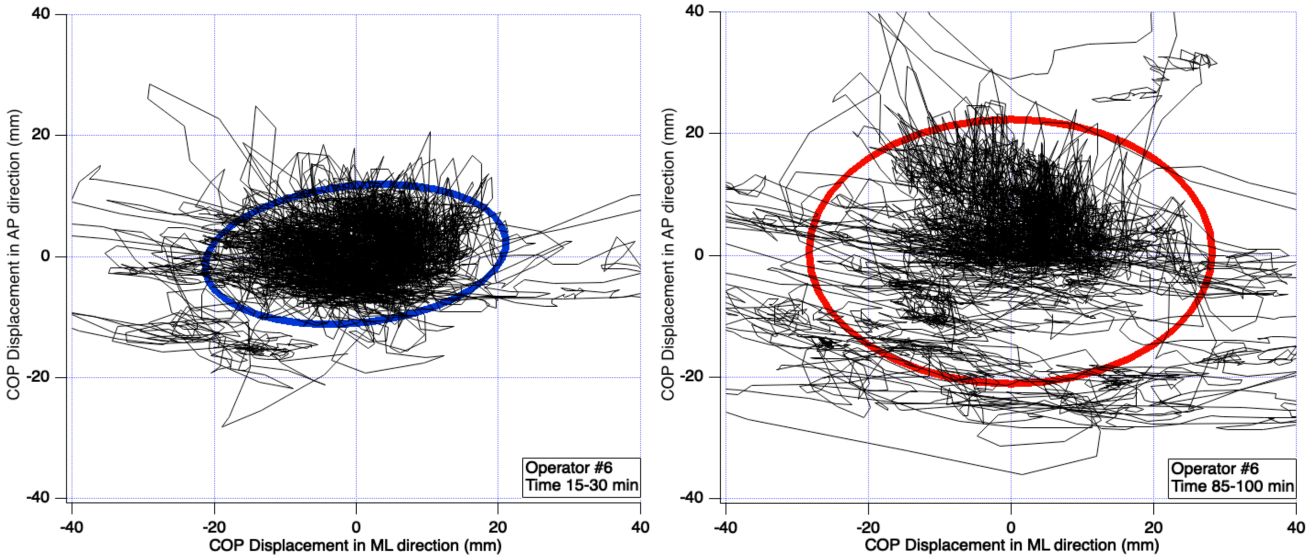

Figure 9.7: Example of sway path and confidence ellipse for one driver at the beginning (15-30min window) and at the end (85.100 min window) of the driving session

al., 2014; Leban et al., 2017; Sammonds et al., 2017; Leban et al., 2019), where subjects were found to move more with time. Prolonged sitting has already shown to be related to muscle fatigue due to the sustained contraction of back muscles while sitting (Hosea et al., 1976). Back muscle fatigue during sitting is induced in situations where an active posture is maintained, for example in vehicles where visual inspection of the environment, in front or on the sides is required to avoid accidents (Santos et al., 2009), or when prolonged slumped sitting is maintained, and may compromise the stability of the spine (Waongenngarm et al., 2016). Given that, it could be hypothesized that, similarly to what occurs in the case of upright stance, trunk muscles fatigue is able to originate delays in neuromuscular protective reflexes and coordination (O'Sullivan et al., 2006) causing a loss in smoothness of movements (Cortes et al., 2014). In this regard Hendershot et al. (2013) and van Dieen et al. (2012) reported an increase in sway velocity in AP direction after trunk fatigue protocols, while Leban et al. (2017), in their work conducted on quay crane operators cohort in a simulated environment, found that the sway area become significantly larger after more than 2 hours from the beginning of the shift and movements velocities (in both AP and ML directions) after approximately one hour. The less marked increase in sway velocity values over time in our data could depend by the fact that the EC instead the COP was considered in the velocity calculation. This choice was made considering the dynamics of the actual driving task: we wanted to take in account the velocity of rigid shifts only, not including instantaneous fluctuations of the COP, due for example by driving on rough sections of the road.

The increasing trend in postural changes over time has already been reported by previous authors in tests performed under ecological or simulated conditions (Fenety and Walker, 2002; Na et al., 2005; Le et al., 2014, Cascioli et al., 2016; Fasulo et al., 2019). The particular results here reported, show that drivers perform a greater number of ICM in the ML with respect to the AP direction. However, the trend over time shows a greater increase in AP direction with respect of the baseline value, indicating bigger modifications in postural strategies on this direction. This is probably to be due to the fact that mid-lateral movements are most likely lead to the driving task (manage the steering wheel, looking to the mirrors etc.) while AP movements are more dependent on the particular postural strategy adopted.

An increase in ICM and sway parameters could be explained in two different ways or with a combination of the two. i). It could represent a specific strategy adopted in order to cope with discomfort onset. ii). Fatigue arises and could significantly impair drivers' postural abilities. As regard as i), Le et al. (2014) suggested that individuals forced to spend long time in sitting posture continuously attempt to alleviate the discomfort through subtle movement. This interpretation is in line with Hermann and Bubb's (2007) theory, who hypothesized that drivers move unconsciously in order to relieve pressure on more compressed body parts which cause them discomfort. As the duration of sitting increases drivers reach the discomfort threshold more quickly as time progresses, thus fidget more frequently (Sammonds et al., 2017). ii), It is known that, in an orthostatic position, body sway reflects the overall performance of the postural control system and the amount of muscular activity necessary to achieve the required stability (Cameron and Huisinga, 2013; Serra-Ano et al., 2015). Thus, an increase in sway is likely to indicate that, due to a deterioration in postural control system performance, the amount of muscular activity necessary to achieve stability also increases with time. In particular, Serra-Ano et al. (2015) reported that COP velocity reflects the neuromuscular activity necessary to maintain balance, so alterations in COP velocity may be explained as a consequence of fatigue onset. Previous researchers (Vuillerme et al., 2007) reported that an increase in movements amplitude in a trunk-fatigued condition with respect to a no-fatigued condition can be seen. Despite cited results refer to conditions different from what considered in the present study (i.e. upright posture), some researchers consider reasonable that, similarly to that case, localized trunk fatigue can induce to a proprioceptive deficit that affects neuromuscular reflexes and coordination also in a seated posture (O'Sullivan et al., 2006). In this regard Vette et al. (2009) compared upright and sitting sway patterns, finding a correlation in sway velocity between the two tasks; nevertheless the author suggested that high caution needs to be done in comparing sitting and standing tasks, as important differences in the motor-control schemes involved do exist. An plausible explanation for sway velocity increase over time may consist in the fact that the stabilizing muscles activity could be altered by the onset of fatigue (Cortes et al., 2014), thus resulting in an impaired effectiveness of overall postural control.

Regarding sway maximum displacements and path increase, our results, although in contrast with Sammonds et al. (2017) who didn't observe an increase in seat fidgets magnitude with duration of driving, appear to be quite consistent with Leban et al. (2017). The discrepancy between our results and those reported by Sammonds et al., (2017) is probably due to the design of the method employed by those authors, where movement magnitude was defined by the type of movement (i.e. only leg, only torso or whole body movements) and assessed by mean of video analysis: the authors acknowledged the limitations of such approach, stating that if a method assessing magnitude of movement in terms of distance and duration would have been implemented, there would have been a chance that very different results may be observed. It is noteworthy that some movements (both in AP and ML directions) may reflect the actual driving task requirements (i.e. move the steering wheel during turns, check in the mirrors, operate the controllers to allow access for passengers, etc.) and that a non-homogeneous distribution of turns, stops and straights (for example, concentrated at the beginning rather than at the end of the trial and vice versa) could influence driver's movements. In this regard the particular set up employed in the present study mitigates this phenomenon, as each route was travelled the same amount of times in both directions: in this way an increase or decrease in parameters value is more likely to reflect the operator's behavior and not the effect of the particular route travelled. It appears therefore reasonable to this author to affirm that the excess of movement noticed over time may be mostly caused by the onset of fatigue and/or discomfort.

The existence of significant displacements of the EC in AP direction as the shift progresses detected in our sample is in contrast to what observed by Albert et al. (2014); nevertheless, the same behavior has been reported by Jin et al. (2009) who saw that after long time driving drivers tend to "slip forward" on the seat, shifting in this way the COP forward on the seat pan. The author explained this phenomenon suggesting that drivers progressively “slouch” (slide/slip forward) in their seats over time in an attempt to reduce their driving fatigue by looking for extra support from the seatback (Hendriks et al., 2006). Contrary to what reported by Jin et al. (2009), who observed a shift of the body towards the left side of the pan as time progressed, we did not find any significant trend in ML direction, even if the p value was borderline (p=.077). It could be hypothesized that this discrepancy is due to the fact that the present study was conducted on real routes while the latter was in a laboratory setup. The presence of vibrations from road-vehicle may improve peripheral and leg blood flow (Lythgo et al., 2009; Games et al., 2015) and left-right turns may indirectly help to periodically relief contact pressure in the buttock region, influencing driver’s need to bend laterally on the seat. Additionally, the particular seat ergonomics of professional cockpits may give a sufficient external support both to the left and the right leg, whereas less support is given by the foot implied in the pedal control.

Another important aspect must be considered, namely the high cognitive load requested to bus drivers to guarantee the safety of the transport. Fatigued drivers have been demonstrated to face greater attention demand with respect to no-fatigued ones (Liu et al., 2009) and this could be considered as a cofactor influencing the effectiveness of postural control. In this sense, previous studies reported significant increases in sway when a cognitive task was added both while standing (Mujdeci et al., 2016) and maintaining a sitting posture (Igarashi et al., 2016).

Finally, it is interesting to highlight how the perceived discomfort levels referred to the body districts are related with time. Upper Back discomfort grows over time as Sitting Bones region; passing from the Lower Back to the Edge of Seat Contact we can see that curve slopes gets higher. This fact may be done to the particular ‘slouched’ posture assumed by drivers after some time spent driving: slipping forward may cause the operator to no longer have contact of the Low back area with the seat; in this way, regions in direct contact with the seat and subjected to high contact pressures seem to be more sensitive to discomfort increase over time with respect to those areas subjected to lower or no pressures.

Some limitations of the study must be acknowledged. Firstly, we did not include in the analysis some anthropometric features of the participants which might influence trunk sway as height and weight. Secondly, given the nature of the study, we were unable to set test start and end times, therefore some trials were performed under different light and –probably– traffic conditions. Finally, as this was a real-world study, drivers were highly engaged in their work paying high attention to the road, thus only three values per-subject on perceived discomfort were collected in such a way to minimize the distractions for drivers. For this reason, we only evaluated the discomfort trend over time and did not deeply studied its relationship with trunk sway variables. Moreover, some quantitative data should be collected on drivers fatigue in order to establish if a direct link with sway parameters could be made. In particular it would be interesting to evaluate how different types of fatigue change over time (fatigue caused by discomfort, musculoskeletal fatigue due to prolonged trunk muscles exertion and cognitive fatigue) to assess if and in which order postural sway may be influenced.

9.5 Conclusion

In summary, the results of the present study revealed an increase in ICM, sway amplitude and velocities, suggesting the adoption by drivers of particular postural strategies in order to cope with discomfort onset and/or fatigue-induced deterioration of postural control abilities. Although the relationship between ICM and discomfort is quite established, it remains unclear the exact association with trunk sway, fatigue and potential increased musculoskeletal disorders risk. Sway parameters also seem to be related with discomfort, as they show a similar trend over time. Such a non-intrusive technique allows to assess trunk oscillation over time and may be incorporated in sensorized cockpits that enable the remote and continuous monitoring of drivers' conditions during the shift, along with the ICM computing. This could possibly lead to work schedule modifications in order to prevent or alleviate discomfort and fatigue onset. Further studies on larger cohorts are necessary to fully investigate the relationship between trunk sway, discomfort and fatigue level along with postural performance deterioration. Finally it would be interesting to study if results here obtained are generalizable to drivers categories other than bus drivers.

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Chapter 10

Postural strategies among office workers during prolonged sitting over actual workshift

Office workers are constantly forced to adopt prolonged constrained sitting posture, a fact that can result in increased risk for adverse health outcome such as cardiovascular and work-related musculoskeletal diseases. Although office work has become widespread in the last decades, there are scarce information about the postural strategies adopted by workers , especially under actual conditions. This study aimed to characterize modifications in sitting behavior, in terms of contact pressure, trunk sway and seat fidget or in chair movements (ICM) in office workers during actual shifts using a pressure-sensitive mat placed on the seat.

10.1 Introduction

Sedentary behavior has increased over last decades due to the growing number of individuals who spend long periods in a seated position both at work and during leisure time (Jans, Proper, & Hildebrandt, 2007; Saidj et al., 2015; Bontrup et al., 2019; Hadgraft et al., 2015). With the rapid growth of modern technology, sitting has in fact become the most common posture in workplaces worldwide (Li & Haslegrave, 1999). Today's office worker performs many tasks, such as computer use, in person or web based meetings, reading, and communicating via phone, web or email, all of which are largely done while sitting (Waongenngarm, Rajaratnam, & Janwantanakul, 2016). However, sitting for long periods of time comes at a cost: in fact being sedentary has been associated with numerous cardiometabolic and musculoskeletal disorders as reported in Chapter 2.

Recent studies have provided evidence that sedentary behavior is associated with negative health connotations, as already mentioned in Chapter 2, reporting the existence of a relationship between prolonged sedentary bouts all-cause morbidity and mortality (Carter, Hartman, Holder, Thijssen, & Hopkins, 2017; Healy et al., 2008). A reduction in musculoskeletal disorders, specifically in LBP, may result in reducing the cost associated with their treatment and it could save companies the costs of managing affected employees.

Due to the potential economic and social benefits from reducing low back pain (LBP) incidence among sedentary workers, many researchers focus their attention on the risk factors, with particular emphasis on activities associated with the onset of early symptoms (Riihimaki, 1991), in order to set up specific prevention programs (Lis, Black, Korn, & Nordin, 2007). From these evidences, the study of discomfort in relation to prolonged sitting, may reveal important aspects about the transition from discomfort to pain.

As seen in the previous chapters, discomfort has been proven associated with sitting postural movements, as several studies found a positive relationship between discomfort and the frequency of postural changes during computer work (Fenety & Walker, 2002; Liao & Drury, 2000; Vergara & Page, 2002). This phenomenon can be explained by the fact that virtually any posture, even though suitable from a biomechanical point if sustained for a long period, turn to uncomfortable and lead to the necessity of varying it (Vergara & Page, 2002).

Based on such evidences, the concept of “dynamic sitting” (i.e. a status in which sitting positions are continuously modified), has gradually replaced the general belief which described the ideal sitting position “as upright as possible” (Zemp, Fliesser, Wippert, Taylor, & Lorenzetti, 2016; Zemp, Taylor, & Lorenzetti, 2016). As a result, postural variability including regular small movements (microshifts) on the chair (Aarås, Westgaard, & Stranden, 1988; Davis, Kotowski, Sharma, Herrmann, & Krishnan, 2009; Pynt, Higgs, & Mackey, 2001; Srinivasan & Mathiassen, 2012; Vergara & Page, 2002) as well as changes in posture between sitting and standing (macroshifts) (Genaidy, Al-Shedi, & Karwowski, 1994; Karakolis, Barrett, & Callaghan, 2016; Liao & Drury, 2000; McLean, Tingley, Scott, & Rickards, 2001) are considered to be beneficial for perceived discomfort and consequently useful for the purposes of LBP prevention, as they allow to reduce loads on the spine and soft tissues in direct contact with the seat.

Understanding the relationship between the way people sit and the associated discomfort is important for developing strategies aimed to optimize both productivity and wellbeing.

As previously mentioned, in previous studies different measurement technologies have been employed to objectively characterize sitting behavior such as video analysis (Womersley & May, 2006), accelerometers (Ryan, Grant, Dall, & Granat, 2011), optoelectronic motion capture systems (Dunk & Callaghan, 2005), force sensors (Yamada, Kamiya, Kudo, Nonaka, & Toyama, 2009; Zemp, Fliesser, et al., 2016) and pressure sensors (Zemp, Taylor, et al., 2016). In particular, pressure sensors are characterized by several interesting advantages, like the relative low-cost and the negligible influence on the subject during measurement , thus allowing high reliability for assessing individual sitting behavior (Yamada et al., 2009; Zemp, Fliesser, et al., 2016). Pressure mats are easily attachable and therefore offer a practical solution for analyzing the sitting behavior of participants on their own chair (Bontrup et al., 2019).

Based on the above-mentioned considerations, the aim of this study is to investigate microshifts and movement patterns in individuals required to perform computer work, and to assess the existence of possible relationships between microshifts and discomfort over time.

10.2 Methods

10.2.1 Participants

Participants (N=28) were recruited among students and personnel from the University of California at Berkeley (Berkeley, USA) using flyers posted around the campus. Additionally, employees from the School of Public Health of the same University were recruited through emails. All participants were aged between 18 and 65 years, worked at least 30 hours/week on the computer, and had to have access to an adjustable (sit:stand) workstation. They were also free from any active musculoskeletal pain or medical condition at the motor system. This study was approved by the Committee for Protection of Human Subjects at the UC Berkeley.

10.2.2. Procedure

All data were collected at the participants' workspace or in an enclosed office (equipped with the same chair and desk) at Berkeley Way West, a recently constructed building equipped with standardized adjustable desks and chairs. Tests were scheduled at the beginning of the participants' work-shift, either in the morning (N= 15) or in the afternoon (N=13), depending on subject's schedule. The total protocol took approximately three hours per participant. Upon arrival, participants signed an informed consent form, were asked to complete a survey on their daily habits and main anthropometric data was collected. Then, they were asked to set their sit: stand workstation according to their preferred sitting settings (i.e. the one they regularly use every day) and a pressure sensitive mat was placed on the chair seat-pan. Prior to start the data collection, participants were asked to sit, make the final adjustments on their workstation and sit using seat back and arm-rests while starting the recording. Contact pressure was continuously recorded for 3-hours while participants were working at their computer during their regular work-shift. During the test, participants were allowed to take short breaks if needed: they were asked to stay seated unless they needed a break. As the number and duration of breaks was only calculated in the post-processing analysis, the test duration was set up to 3 hours to ensure that at least 2 hours of sitting data was collected. Participants were also required to provide subjective discomfort ratings every 30 min using a 2-part questionnaire where part 1 focuses on local discomfort (upper back, lower back, sitting bones, buttock area and edge of the seat contact) and included a 6-point discomfort scale (ISO 2631-1-2003), while part 2 describes the overall discomfort as described in Chapter 6.

Experimental Set-up

Figure 10.2: Participant during a testing session.

Contact pressure data at the body-seat interface was obtained by means of a pressure-sensitive mat (Tekscan 5330E, 471.4 x 471.4 mm active area, 1024 sensing elements arranged in a 32 x 32 matrix) which collected data at 10 Hz sampling frequency (Fig. 10.1). The pressure-sensitive mat was connected to a two-port hub (Tekscan Versatek) and then to a PC via USB connection. Before each test, the mat was calibrated as described in Chapter 6.

10.2.3. Measures

Outcome Variables

Time-series data for mean pressure (MP), antero-posterior (AP) and medial-lateral (ML) center of pressure (COP) position were extracted using the Tekscan Conformat Research Software v.7.20. Starting from raw pressure data the sway parameters and ICM were calculated

(Era & Heikkinen, 1985) across time windows of 2.5 seconds and averaged over 15-min blocks, as previously described in Chapter 6 and Chapter 7. Data related to the first minute before and after any break were discarded in order to remove any possible artifact originated by the sitting and seat-adjustment phases.

10.2.4. Statistical Analysis

All calculations were performed with a dedicated custom software developed under the Matlab® environment (MathWorks, Inc, Natick, MA, USA). As previously mentioned, outcome measures were summarized within 15-min intervals (Anne Fenety, Putnam, & Walker, 2000). Participants were stratified into *breakers* if they had at least one break lasting more than 1min during the test and *prolongers* if no breaks were taken.

The relationship between outcome variables and time was investigated using the Pearson product moment correlation for continuous data (sway and pressure variables) or the Spearman correlation coefficient for categorical data (discomfort).

Sway and pressure variables

In order to assess the existence of possible differences over time in outcome variables values during the 2-hour shift and to detect any particular difference between the two groups, a two-way analysis of variance for repeated measures (MANOVA RM), performed using the IBM SPSS Statistics v.26 software (IBM, Armonk, NY, USA) was used, setting the time and the group as independent variables. In all tests the significance level was set at p = 0.05 and size effect was assessed using the eta-squared coefficient. Multiple comparison tests vs. baseline value of variables (relative to the first 15-min interval) were performed. If significant, the follow-up pairwise comparisons were performed using the Bonferroni post hoc test to adjust for multiple comparisons.

Discomfort Surveys

A two-way multivariate analysis of variance for repeated measures (MANOVA RM) was carried out, following verification of parametric model assumptions in order to find any difference on perceived discomfort ratings over time (within subjects design) and between groups (*breakers* vs *prolongers*): the independent variables were the time and group while the dependent variables were the subjective discomfort ratings. The level of significance was set at $p = 0.05$, and size effect was assessed using the eta-squared coefficient.

10.3 Results

Demographic and anthropometric data are reported in Tab. 10.1. The mean age was 33.23 (9.37) and the average working schedule was 42.07±4.33 h/week.

Table 10.6: Anthropometric features of the participants. Values are expressed as means ± SD.

Participants #	*28 (24 F, 4 M)*
Age (yrs)	33.23 ± 9.37
Height (cm)	163.34 ± 8.37
Body Mass (kg)	69.22 ± 13.87
BMI (kg/m^2)	25.81 ± 3.81
Working hours per week (h)	42.07 ± 4.33

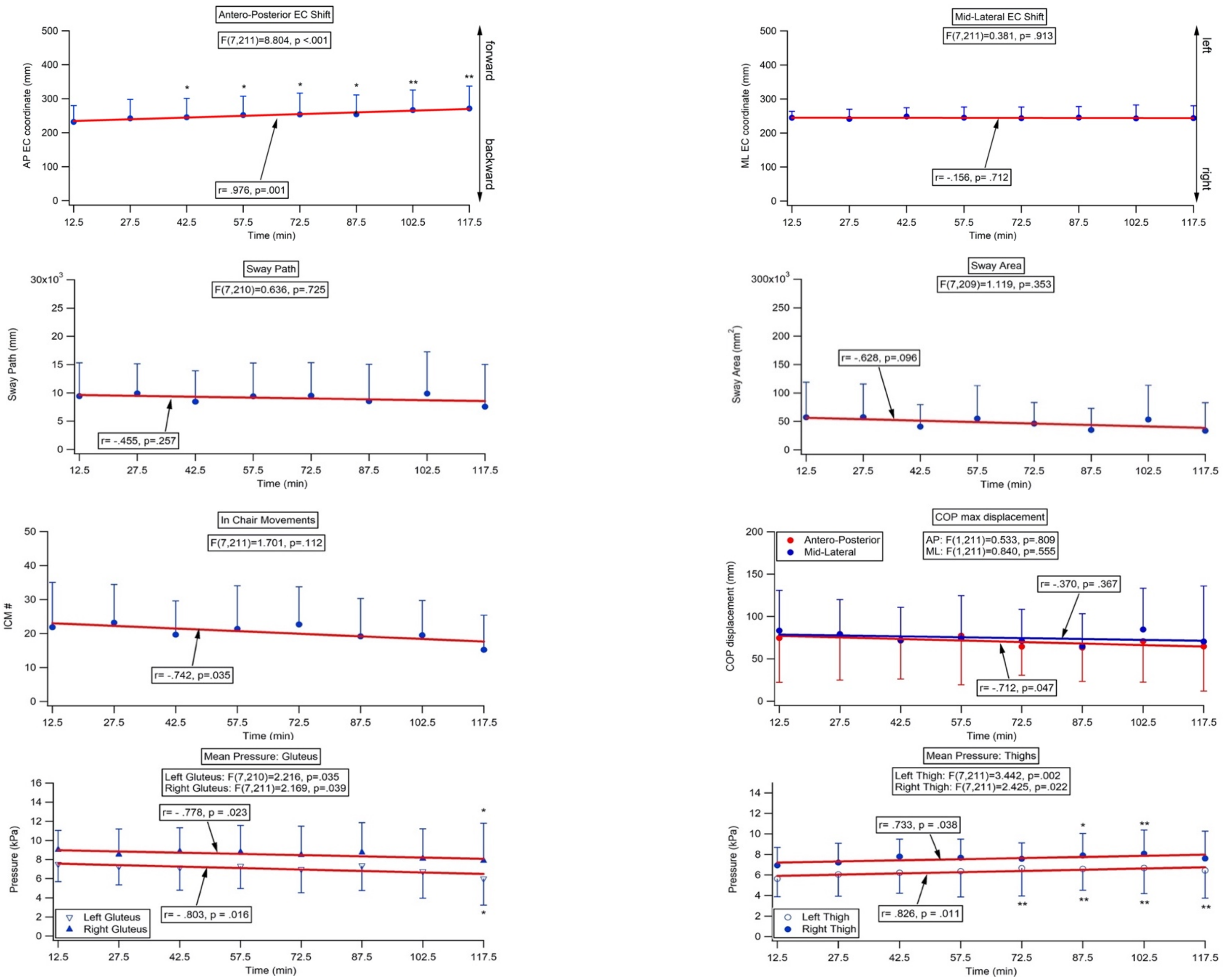

*Figure 10.3: Trends of outcome variables over time. Error bars indicate standard deviations, the symbols * and ** indicate significant differences for comparisons vs baseline (p<.05 and p<.01 respectively)*

10.3.1 Effect of time

Sway and pressure parameters

Pearson correlation test found a significant trend in EC position over time. RM–MANOVA found the values to be significantly different from the baseline after about 40 min. Maximum displacements of COP in AP direction were also found to be negatively correlated with time. A significant negative trend over time was also evidenced for number of ICM performed ($p = .035$). Mean pressure values were found to be negatively correlated with time in the gluteus region ($p = .023$, $p = .016$ for right and left sides respectively) while pressure values in the thighs regions significantly increase over time ($p = .038$, $p = .011$ for right and left sides). In particular, values were significantly different from the baseline after about 70 min from the beginning of the work-shift. Pearson correlation test (r and p values) and RM-MANOVA results are reported in Fig 10.2.

Table 10.7: Spearman's rho coefficients for subjective discomfort ratings vs time

	Time	*ρ*
Upper Back	0.481	0.412
Lower Back	0.609	0.275
Buttock Area	0.733	0.079
Sitting Bones	0.834	0.159
Edge of Seat Contact	0.949	0.014
Overall Discomfort	0.971	0.006

Perceived discomfort

Correlation test results of perceived discomfort vs time and sway parameters values are reported in Tabs. 10.2 and 10.3 respectively. RM-MANOVA revealed a significant effect of time for Buttock Area [F(4,109) = 6.233, p = .001] and Overall perceived discomfort [F(4,109) = 3.550, p = .010]. No significant effect of time was found for other discomfort ratings: Edge of Seat Contact [F(4,109) = 0.892, p = .473], Upper Back [F(4,109) = 1.375, p = .250], Lower Back [F(4,109) = 0.613, p = .654], Sitting Bones [F(4,109) = 1.290, p = .281].

10.3.2 Group effect

Sway and pressure parameters

MANOVA RM revealed a significant effect of group for SA, SP and COP max Displacement in AP and ML directions. (Fig. 10.3).

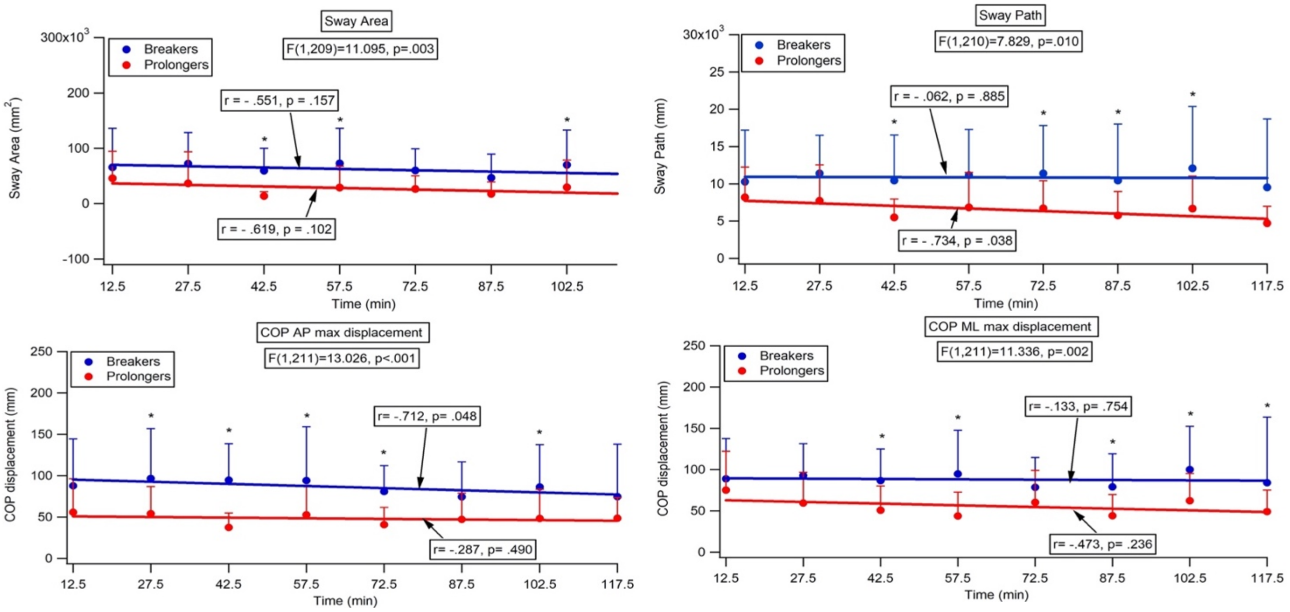

*Figure 10.4: Trends of groups' outcome variables over time. Error bars indicate standard deviations, the symbol * indicates significant differences for comparisons vs baseline (p<.05)*

*Table 10.3: Pearson Correlation coefficients for subjective discomfort ratings vs sway and pressure parameters. The symbols * and ** indicate significant differences for comparisons vs baseline (p<.05 and p<.01 respectively).*

	Group	***Sway Path***	***Sway Area***	***COP AP disp***	***COP AP disp***	***MP***	***MP*** $_{\text{Left Gluteus}}$	***MP*** $_{\text{Right Gluteus}}$	***MP*** $_{\text{Left Thigh}}$	***MP*** $_{\text{Right Thigh}}$	***ICM*** $_{\text{Antero Posterior}}$	***ICM*** $_{\text{Mid Lateral}}$	***ICM***
Upper Back	**All**	-0.062	-0.152	0.185	-0.299	0.664	-0.190	-0.194	0.612	0.499	-0.202	-0.174	-0.175
	Plg	-0.396	-0.419	-0.447	-0.671	0.240	0.445	0.194	0.186	0.128	-0.277	-0.367	-0.283
	Brk	0.297	0.067	-0.071	0.032	0.543	-0.191	-0.146	0.501	0.228	-0.388	-0.065	-0.277
Lower Back	**All**	-0.502	-0.666	-0.874	-0.713	0.525	-0.044	-0.356	0.565	0.528	-0.743	-0.793	-0.796
	Plg	-0.157	0.098	-0.289	-0.289	0.463	-0.082	0.068	0.594	0.306	-0.296	-0.084	-0.332
	Brk	-0.255	-0.713	-0.805	-0.735	0.250	-0.106	-0.278	0.509	0.206	-0.667	-0.823	-0.853
Sitting Bones	**All**	**-0.546**	-0.804	-0.677	-0.797	**0.954***	-0.355	-0.520	**0.968****	**0.939***	**-0.922***	-0.862	**-0.905***
	Plg	**-0.744**	-0.471	-0.205	-0.564	**0.920***	0.228	-0.327	**0.864**	**0.958***	**-0.485**	-0.659	**-0.637**
	Brk	**-0.884***	-0.754	0.060	-0.771	**0.746**	0.097	0.156	**0.769**	**0.658**	**-0.177**	-0.690	**-0.509**
Buttock Area	**All**	-0.527	-0.776	-0.483	-0.706	**0.972****	-0.428	-0.484	**0.967***	**0.969***	-0.868	-0.767	-0.821
	Plg	-0.874	-0.686	-0.224	-0.671	**0.883***	0.567	0.144	**0.769**	**0.738**	-0.752	-0.810	-0.832
	Brk	-0.236	-0.685	-0.111	-0.236	**0.839**	-0.629	-0.511	**0.905***	**0.996****	-0.669	-0.632	-0.672
Edge of Seat	**All**	-0.051	-0.384	-0.597	-0.402	0.683	-0.591	-0.783	0.787	0.759	-0.697	-0.532	-0.638
	Plg	-0.774	-0.561	-0.224	-0.671	0.853	0.380	-0.147	0.779	0.822	-0.540	-0.696	-0.660
	Brk	-0.546	0.178	-0.660	0.084	-0.585	-0.029	-0.238	-0.412	-0.572	-0.240	0.032	-0.122
Overall	**All**	-0.225	-0.585	-0.741	-0.533	**0.786**	-0.630	**-0.811**	**0.888***	**0.896***	**-0.878**	-0.701	-0.814
	Plg	-0.820	-0.566	-0.300	-0.700	**0.946***	0.338	**-0.207**	**0.856**	**0.943***	**-0.591**	-0.743	-0.729
	Brk	-0.382	-0.545	-0.876	0.073	**0.082**	-0.782	**-0.895***	**0.737**	**0.417**	**-0.956***	-0.616	-0.804

Perceived discomfort

Effect of group on subjective discomfort ratings has been reported on:

- Sitting Bones [F(1, 109) = 5.580, p = .028]
- Edge of Seat Contact body regions [F(1, 109) = 4.789, p = .041]
- Trend over time of Overall perceived discomfort are shown in Fig. 10.4.

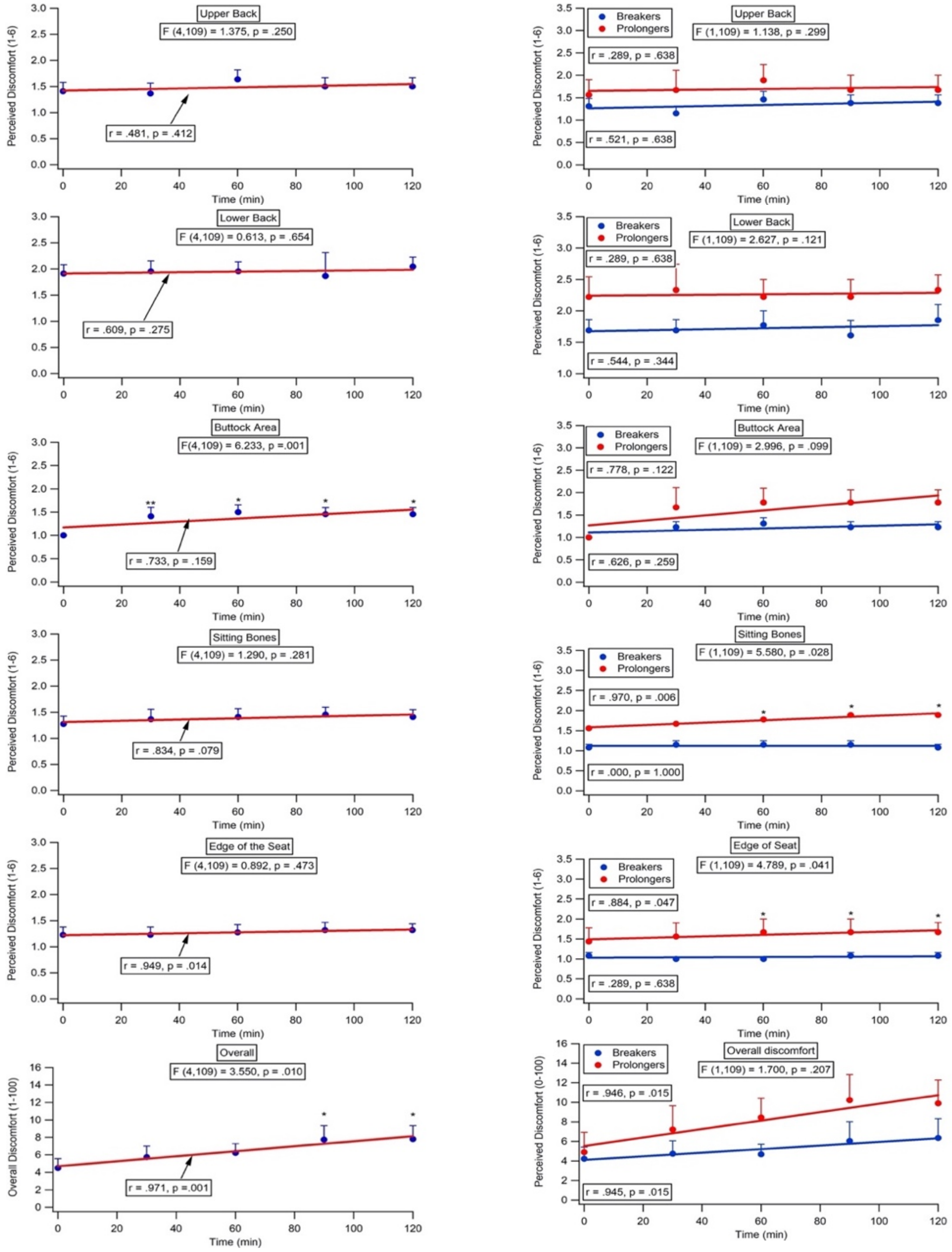

*Figure 10.5: Trends of perceived discomfort ratings over time (on the left are reported data referred to all subjects, on the right data are stratified by group) . Error bars indicate standard deviations. On the left the symbols * indicate significant differences over time vs control (first 15 minutes of the shift), on the right the symbol * indicates*

10.4 Discussion

This study focused on sitting strategies and discomfort during long-term actual work in a cohort of professional office workers. To do that we evaluated the body-seat interface contact pressure, trunk sway and postural adjustments performed over time in order detect any modifications associated with work shift progression and/or discomfort onset. We also investigated if any difference in the above mentioned parameters existed among subjects characterized by different sitting behavior during the shift (i.e. staying seated vs making short breaks during the shift). Generally speaking, our results show an increasing trend for perceived discomfort while, contrary to what expected, trunk sway parameters and ICM show a flat and a decreasing trend respectively as shift progressed. However, significant changes in subjects posture were indirectly indicated by EC coordinate in AP direction: in fact, as time progressed the EC significantly shifted forward. This fact may indicate the adoption of two possible strategies: subjects slouch in the chair, slipping their buttock forward, or they slump their posture in such a way to forward their trunk, thus loading more weight on the thighs region, causing the forward shift of the COP and, consequently, of the EC. Contact pressure values were found to change differently in thighs with respect to gluteus region: in particular pressure increased in thighs region while decreased in gluteus region over time, as a likely consequence of the EC forward shift (or vice versa). Finally, it was possible to detect different sitting behaviors between subjects who adopted different working strategies: prolonged sitting or reduced sitting bouts with short breaks.

To the authors’ knowledge, to date few data are available on the combination of the three sets of parameters investigated here (i.e. postural sway, pressure distribution and ICM) assessed during long term work-shifts of office workers in real working environments.

10.4.1 Effect of time

The significant forward shift of the COP as the workshift progresses may indicate a general change in sitting behavior with time. In particular, this phenomenon may be the consequence of two main strategies: subjects begin to lean forward or to adopt a slumped sitting posture after they've been sitting for about 40 minutes. This change reflects also in mean contact pressure values, which decrease in the gluteus and increase in the thighs region. The same phenomenon, in particular the slumped sitting posture, was previously reported by Akkarakittichoke & Janwantanakul (2017) in their study on office workers during 1 hour of continuous sitting. In particular, subjects were found to change their posture after 30 min, which is a value in good agreement with what we observed in the present study. In fact, a time of 40 min was necessary to detect significant changes in EC coordinates and 60 minutes for pressure distribution. Even though previous authors associated the forward oriented postures – leading to increased loads on the spine and soft tissues (B. J. G. Andersson & Ortengren, 1974; B. J. Andersson, Ortengren, Nachemson, Elfström, & Broman, 1975; Bhatnager, Drury, & Schiro, 1985; H. J. Wilke, Rohlmann, Bergmann, Graichen, & Claes, 2001; Hans Joachim Wilke, Neef, Caimi, Hoogland, & Claes, 1999) – with the tendency fidget more over time, we did not find an increase in ICM (or seat fidget movements), SP and SA over time. This can be due to the fact that, in this particular test, operators may have progressively shifted their trunk forward, but the postural adjustments were always too small to be classified as an ICM. Thus, it was only possible to detect the most noticeable effect, namely the change in mean pressure over the body regions and in COP coordinate. The fact that ICM, SP and SA all decrease over time indicates that workers started to adopt a more rigid posture with time, at the same time forwarding their trunk or slumping their posture in the chair. In practice, it is likely that workers tend to perform a greater number of postural movements or adjustments at the beginning of the shift in an attempt to find the best position and, once the correct one is found, they only make small adjustments until the break. This result is similar to what reported by (Nakane, Toya, & Kudo, 2011), who performed sitting posturography on subjects under fatigued and non–fatigued conditions. These authors reported that user's posture is the most stable when he/she is tired, so the particular behavior shown by subject in our study may be induced by fatigue or tiredness. This behavior resulted also in an increase in perceived discomfort level, especially in the distal extremities, with increasing ratings passing from upper back to the edge of seat contact, where the correlation with time was stronger.

10.4.2 Group effect

Sway parameters were found to be somehow affected by individual's behavior. In fact, SA, SP and COP maximum displacement (both in AP and ML directions) showed significant differences between *breakers* and *prolongers*. The difference is clearer considering the Sway Path parameter: at the beginning of the shift, the two groups show similar path, but its trend changed markedly as time progresses. In particular breakers show almost the same SP pattern over all the workshift, while prolongers start to fidget less over time approximately after 42.5 min from the beginning. This may indicate that periodical breaks could have an influence in inducing people to be more active also while sitting, and this, as seen, may lead to a number of beneficial health outcomes.

Working behavior influenced also the perception of discomfort, with significant differences between the two groups. In particular, values were higher for *prolongers* in the sitting bones and edge of seat contact regions, probably due to the fact that these are the two regions where contact pressure values are higher. Pauses may help breakers in partly restore their initial wellbeing sensation, alleviating sustained pressure under the buttocks (Bontrup et al., 2019; Søndergaard, Olesen, Søndergaard, de Zee, & Madeleine, 2010; Vergara & Page, 2002; Zemp, Fliesser, et al., 2016; Zemp, Taylor, & Lorenzetti, 2015; Zemp, Taylor, et al., 2016). In this regards, our findings are in agreement with previous studies which reported tendencies towards more static sitting behaviors (i.e. less fidgeting and longer periods of uninterrupted sitting) in participants perceiving pain and discomfort or suffering from chronic LBP (Akkarakittichoke & Janwantanakul, 2017; O'Keeffe, Dankaerts, O'Sullivan, O'Sullivan, & O'Sullivan, 2013; Vergara & Page, 2002; Womersley & May, 2006; Zemp, Taylor, et al., 2016). Prolongers may perceive pain, and this induces them to fidget less and adopt a rigid posture, which in turn increases the level of perceived discomfort, in a circular process.

Some limitations of the study must be acknowledged. Firstly, we did not use a pressure mat in the backrest and we cannot guarantee that the forwarding of the COP with increased pressure in the thighs region is due to a forward bending of the trunk or a slumped sitting posture. These two behaviors expose workers to different levels of risks. Secondly, we did not have any information on cognitive load of the actual task performed by subjects while working on the computer and this could have influenced our results: making too complex tasks or being highly /concentrated in the task may lead to adopt rigid postures and perform less postural adjustments, somehow making subjects “forgetting” to move. In this regard previous authors studied the effect of a feedback signal prompting workers to move more while working at their workstation, in order to prevent discomfort and musculoskeletal disorders at an early stage, by changing sitting patterns among office workers (Davis et al., 2009; Goossens, Netten, & Van Der Doelen, 2012; Haller et al., 2011; Roossien et al., 2017). In particular, Roossien et al., (2017) found that after turning off the feedback signal, a slight increase in sitting duration can be observed, accompanied to a decrease in optimally supported posture and musculoskeletal discomfort, even though these changes were quite small.

10.5 Conclusion

In summary, the results of the present study revealed a decrease in sway parameters and ICM performed over time, along with the adoption of a more forward bended trunk posture and increased perceived discomfort. It was also possible to characterize sitting postural strategies of subjects behaving differently in terms of sedentariness: breakers and prolongers. Such a non-intrusive technique that allows to assess trunk oscillation and postural changes over time may be incorporated in a sensorized workstation that enable the remote and continuous monitoring of workers' conditions during the shift. This could possibly lead to set up reminders and feedback on motor activity in order to prevent or alleviate discomfort and fatigue onset. Further studies on larger cohorts are necessary to fully investigate the relationship between trunk sway, ICM, discomfort and fatigue level along with cognitive load influence on posture. Finally future studies are needed to assess the importance of cognitive load on sitting postural strategies and to better investigate differences among breakers and prolongers over extended working shifts.

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Chapter 11

Conclusion

Interaction between individuals and seat plays an important role in determining the overall comfort state. Although sitting work (and its possible negative consequences) has becoming widespread in the last decades, the existence of possible effects associated with prolonged sitting postures in terms of postural strategies has been scarcely investigated under actual working conditions. In this study, we attempted to characterize the possible modifications in sitting behavior during actual prolonged shifts, in terms of trunk sway and in chair movements (ICM) induced by the time, the level of perceived discomfort and, probably, task-induced fatigue.

The first aim was to validate a reliable algorithm which could clearly detect postural shifts while sitting, possibly applicable in a wide range of applications, so to obtain a reliable estimation of ICM. Thanks to the use of pressure sensitive mats, starting from the calculation of trunk sway parameters, it was possible to develop such algorithm, which allows detecting postural shifts on the seat-pan, in both AP and ML directions. In particular, the developed algorithm was based on the displacement of the confidence ellipse's center and its features were not affected by sharp but sporadic changes of COP position, caused for example by sudden random vibrations from the external environment.

The second aim was to investigate trunk sway parameters, ICM and their relationship with discomfort over prolonged work-shifts performed in real working conditions. The results reported in Chapter 8 and Chapter 9 demonstrated the feasibility of application of such technique to actual driving conditions and for long-term monitoring. By means of the parameters derived from this sensor it was possible to characterize sitting behaviors of professional drivers through the analysis of trunk sway and the ICM trend over time. Changes in posture consequent to discomfort and/or fatigue were clearly detected, also with differences depending on route condition (i.e. urban or extra-urban). In short, all drivers showed an increase in sway parameters and ICM and discomfort during the shift, indicating that discomfort onset and/or fatigue induce changes in postural strategies and deterioration of postural control of the trunk. When considering only homogeneous chunks of continuous driving in the case of urban routes, a difference was highlighted between sway parameters and ICM trend, indicating that these parameters relate to different features of the postural control. Although the exact association with discomfort, fatigue and potential increased musculoskeletal disorders risk remains unclear, ICM seemed to be more related with the first, as they show a similar trend over time.

The results of the third field study, shown in Chapter 10, surprisingly revealed a decrease in sway parameters and ICM performed over time, along with the adoption of a more forward bended trunk posture and an increase in perceived discomfort. By means of the pressure sensitive mat-derived information it was also possible to characterize sitting postural strategies of subjects behaving differently in terms of sedentariness, breakers and prolongers, which exhibited also a different behavior while sitting.

Some discrepancies in the findings obtained among bus drivers and office workers was found and it could be due to the fact that office work is by essence static, while bus driving involves more dynamic tasks (control of the steering wheel and pedals, head movements).

The result of this study should be considered in light of some limitations: first, in the case of the study described in Chapter 8, being this a pilot study to assess the feasibility of monitoring of body-seat interface pressure during a real long-term driving work shift, the size of the tested sample was limited. Secondly, the effect of different anthropometric features, such as height and weight, was not taken into account in our results, and they are known to influence trunk sway amplitude. Additionally, during the driving tests it was not possible to set test start and end times, and therefore some trials were performed under different light and traffic conditions. Since all reported experiments were carried out under real-world conditions, workers were highly engaged in their work, paying high attention to the performed task, and thus, in some cases, only a limited set of data on perceived discomfort were collected, resulting in an impossibility to assess the existence of statistical relationship with sway and ICM.

In summary, such a non-intrusive technique that allows to assess trunk oscillation and postural changes over time may be incorporated in sensorized workstations and cockpits that enable the remote and continuous monitoring of workers' conditions during the shift. This could possibly lead to work schedule modifications in order to prevent or alleviate discomfort and fatigue onset.

Further studies on larger cohorts are necessary to fully investigate the relationship between trunk sway, ICM, discomfort and fatigue level along with cognitive load influence on sitting behavior over extended shifts. It would be interesting to collect some quantitative on workers' fatigue state in order to establish if a direct link with sway parameters could be made. In particular, it would be interesting to evaluate how different types of fatigue change over time (fatigue caused by discomfort, musculoskeletal fatigue due to prolonged trunk muscle exertion and cognitive fatigue) to assess if and in which order postural sway and ICM may be influenced.