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Towards predicting the (dis)comfort performance by modelling: methods and findings

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Towards predicting the (dis)comfort performance by modelling: methods and findings

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Contents

PREFACE

Dealing with discoveries about the unified theory of Physics that might connect General Relativity theory with Quantum Mechanics one, one of the greatest living physicians, Stephen W. Hawking [1], said: "*it may not aid the survival of our species; it may not even affect our life-style. But ever since the down of civilisation, people have not been content to see events as unconnected and inexplicable. They have craved an understanding of the underlying "MAIN ORDER" in the world*".

The investigation of "models" of how the things and the events "work", has always been the motor of all things, in every field of research and also in every action of our lives.

Constructing a model to describe, analyze, evaluate and predict (dis)comfort perceptions is the goal of this PhD thesis. Aspects of the "world of (dis)comfort perception" were investigated, conclusions collected in common laws that govern the interaction between humans and products, and a methodology for comfort driven design was developed.

Reference

1) *Hawking, S.W. (1998), A brief history of time: From the Big Bang to Black Holes, Bantam Dell Publishing Group, ISBN: 978-0-553-10953-5*

Chapter 1

General Introduction

1 General introduction

1.1 From ergonomics to comfort

Since the first appearance of hand-tools, artisans and engineers have attempted to make handwork as comfortable as possible. In the second half of twentieth century, awareness raising by industrialists about ergonomics and safety made the preventive evaluation of workplace ergonomics/comfort an essential element of product/process design. Nowadays, designers and engineers know that a comfortable and ergonomic workplace can improve overall operator performance [1-3], as well as reducing the risk of musculoskeletal diseases and subsequent absence periods and/or insurance issues. Nevertheless, this knowledge is not always easily applied, due to its economic cost and its resultant time to market (TTM) increase.

However, the 'comfort issue' is not strictly related to workplace design. 'Ergonomics' is a Greek term (ἔργον, meaning 'work', and νόμος, meaning 'natural law') whose original meaning is 'the natural law of work'. The first time that this term was used for describing work-related activity was in an 1857 article by the Polish scientist Wojciech Jastrzębowski [4]. Its first English usage is generally attributed to British psychologist Hywel Murrell at the 1949 meeting at the UK Admiralty, which led to the foundation of The Ergonomics Society, with his famous phrase Ergonomics is: 'to fit the job to workers'.

After the Second World War, the concept of 'fitting something to humans' (not only to workers) became a central component of user-centred design (UCD) and human-centred design (HCD). UCD defines humans as 'users' while HCD takes the term 'human' to include all the elements that can interact with humans, even independently of their will, e.g. the environment or emotions. UCD is a broad term used to describe design processes in which end-users influence the way that a design takes shape [5]. It is both a broad philosophy and a method, both of which involve users during the design process. The term 'user-centred design' itself originated in Donald Norman's research laboratory at the University of California San Diego (UCSD) in the 1980s (Norman & Draper, 1986, [6]) following the publication of the seminal book *The Psychology of Everyday Things* (Norman, 1988, [7]). This book contains several suggestions about the design process by those directly involved. In the UCD approach, the 'comfort' variable is intrinsically taken into account by a method that requires several sessions of 'testing with users'. Both usability and comprehensibility tests are utilised to improve users' direct experience; however, no specific comfort-driven design methods were ever set down. In 1987, Ben Shneiderman articulated a similar set of principles in the form of eight golden rules (Shneiderman, 1987, [8]). These were later adapted and popularised by Jakob Nielsen in his heuristics for usability engineering (Nielsen, 1993, 2001, [9,10]). The involvement of users in the design process seems to provide designers and manufacturers with instruments that lead to more effective, more efficient and safer products, as well as contributing to their commercial acceptance and success (Preece, Rogers, & Sharp, 2002, [11]). Nevertheless, the user-centred approach is too limiting and experience-related to allow for the development of a real comfort-driven design method.

The natural landing point of this design issue was hence the human-centred approach. HCD techniques place humans (and their wellbeing) at the centre of the design process. Their main aim is to improve products, processes and the environment to give users a better interactive experience. Both in the fields of health [12] and human rights [13], HCD helps companies and industries to support the development of product/process strategies that improve wellbeing. Recently, HCD artefacts have also become part of companies' development and improvement strategies [14]. Finally, HCD is defined in ISO 9241-210 [15] as 'an approach to interactive systems development that aims to make systems usable and useful by focusing on the users, their needs and requirements, and by applying human factors/ergonomics, usability knowledge, and techniques. This approach enhances effectiveness and efficiency, improves human well-being, user satisfaction, accessibility and sustainability; and counteracts possible adverse effects of use on human health, safety and performance'.

While the Standard was developed for VDT workers, this description goes beyond the concept of ergonomics to include theoretical and practical ideas relating to human wellbeing. In Stavrakos 2015 [16], we find the notion that companies' needs translate into business targets. To stay ahead of the competition, industry aims for products that are comfortable or that can drive the user by means of a comfortable experience. This is true for all products human beings interface with. In addition, discomfort should be prevented in order to reduce pain in the long term (Hamberg et al, 2008, [17]) or reduce dissatisfaction with the product. Scientists, researchers and private companies thus began to consider comfort/discomfort as important factors in their businesses. Simply stated: **user comfort has been translated into revenue targets.** This in turn demands that comfort requirements, seen as functional requirements, are incorporated into products' design parameters – the most significant design challenge of the last twenty years. And this work seeks to play a part in meeting this challenge.

The ***first research question*** of this work is: "Can a comfort driven design method be developed and implemented in the products' improvement process?"[1]

The ***second research question*** is: "If so, what are the laws (νόμος) that allow the modelling of the (dis)comfort perception during an interaction (like user or, more generally, like human)?"

1.2 Design process in the digital era

Since the birth of the human-kind, the design process has been performed by designers through the use of natural laws for advantaging humans in their lives and through the trial and error method and the consequently surviving of the better solution (The Origin of Species, Charles Darwin, 1859 [18]).

After the assessment of the "scientific method" by Galileo Galilei, through the observation of phenomena, the analysis of the data, the research of a common law/function to describe the behaviours, the abstraction of the models trying to reach the required level of repeatability,

Hubka and Eder, in their book about Design Science [19], deal with the origins and evolution of Design Sciences along the centuries.

It seems that, while in Great Britain, since 1851 (Great World Exhibition), several scientists, engineers and designers begun to deal about design methods and design processes, in the rest of Europe and world, only after the Second World War several Design Schools (GB, Italian, France, US, German, etc. etc.) begun to write theories about Design

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[1] It means: what is the right process that bring to the development of a methods to take into account the (dis)comfort issues into the design process?

methods, focusing their effort on two basic approaches: the Inductive (Bottom-Up) and the deductive (Top-Down) ones.

In the thirty years between the 60’ and the 90’, Several Design theories were developed and published like:

- Pahl and Beitz
- Hubka and Eder
- Oshuga
- VDI (German Standard Institute)
- Concurrent Engineering
- Taguchi Method
- 6-sigma Method

Often, those methods were coupled with optimization methods, comparative methods and Logic/Intelligent methods for developing a complete Design Criterion.

Designers work more and more to improve their methods for designing and realizing what they proposed to do. When the industrial revolution came up, several issues about the role of humans in production systems were faced off; the use of natural materials and the creation of new ones for creating new things and improve humans’ life became common and much efforts were done for understanding the natural laws that rule everything.

Many scientists, among ones we like to remember Newton, Euler, Lagrange, Navier, Stokes, Maxwell, Heisenberg, Einstein, Shannon, Turing, Hawkings, and other that can be easily cited, gave the basis and wrote the equations that allow to describe most of the natural phenomena and the materials’ behaviour under different condition. The infinitesimal calculus and the information theory, until the 1940, gave us the instruments to speed up the use of the mathematical methods for improving the design methods in every field of research, in terms of time-costs, precision and effectiveness.

Along the history of the design development, the prototype had a central role in the design process.

The word "Prototype" has its origin in the Greek language: [sec. XVII;. *prōtótypos*, da *protos*, primo + *týpos*, tipo]: a **prototype** is something that is representative of a category of things, or an early engineering version of something to be tested; it always means the first element of a series that allows to perform the main functions for which has been designed. Around the prototype all the phases of the design process have been made and are made also nowadays.

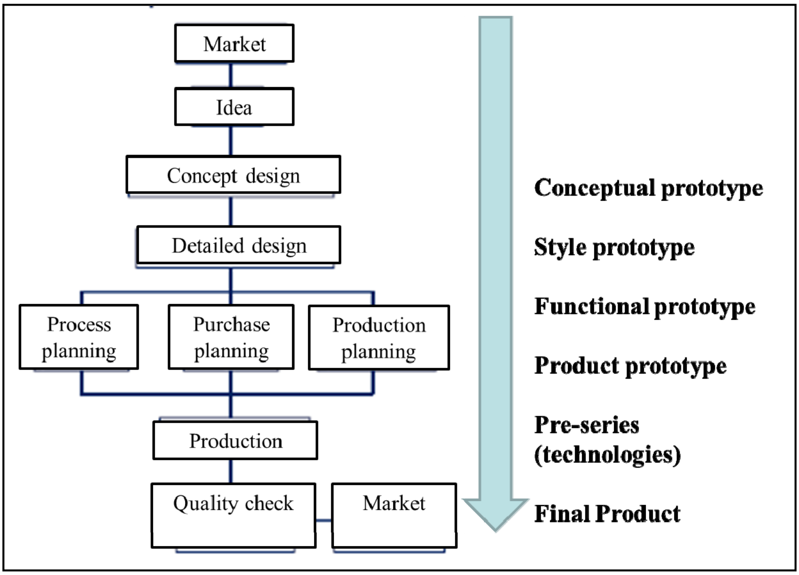

Fig. 1.1: Use of prototypes in the design process

If we want to synthetize the actual design process with few steps (the design process is as diverse as its users. As the basis for this work, we have reduced it to a simplified model), we can take a look to the scheme in Fig. 1.1[20]. In this scheme the needs coming from the market have been transformed into products that go into the market, just respecting the definition of Design given by ASHBY [21]: "Design is the process of translating a new idea or a market need into detailed information from which a product can be manufactured" or given by Delft Design Guide[22]: "designing is a way of thinking and acting that is aimed at understanding and intervening in the world around us through the design of products that aim to help satisfy people's needs and wishes".

As can be seen in the right part of the Fig. 1.1 each step of this simplified design process is corresponding to a "type of prototype", so that each step requires a prototype with a certain Level Of Detail (LOD) for describing its characteristics, its functions and its use.

On this basis, the design process can be seen as a very easy loop-based process as described in Fig. 1.2 Designers have to try to assess and satisfy the market/customers' needs within constraints (given by costs, materials, availability, etc. etc.) by defining the product characteristics both as functional requirements and as design parameters (Suh 1990) [23]. Then, through the use of modern technics for calculation and optimization, designers have to evaluate the product performances and define the design parameters for build the first or several prototypes. Than the prototypes have to be tested in order to understand if the built product fulfils all the required characteristics also for have a guarantee of a sufficient quality level.

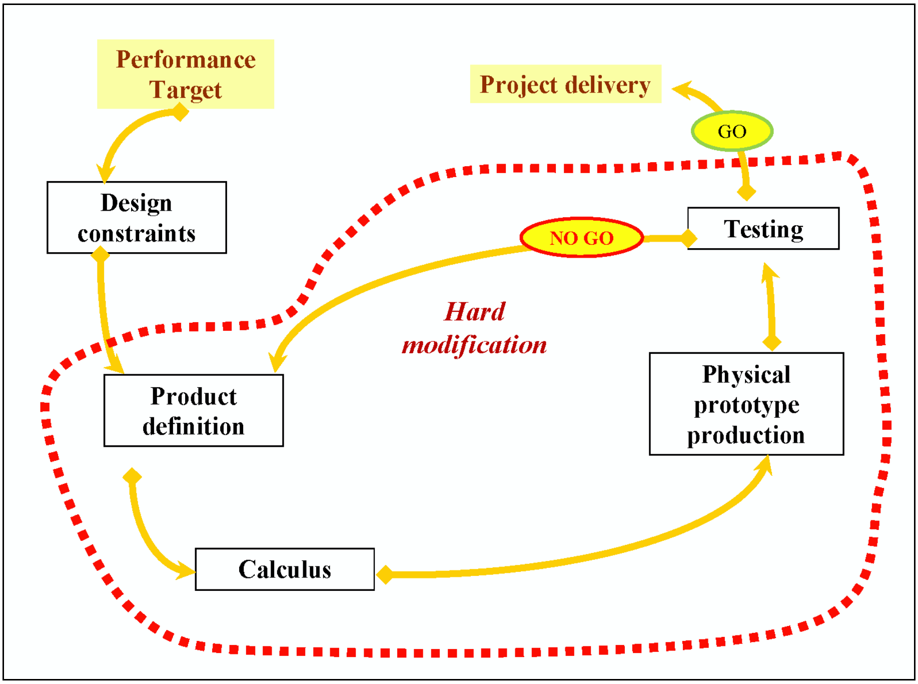

Fig. 1.2: The Design process in the pre-digital era

If all targets are hit, the prototype has a "GO" signals for process design and technology assessment; else, a "NO GO" signal implies that designers have to begin again the design loop, opportunely changing some features of the product. These loops are very time-consuming and expensive in terms of cost for prototyping and of engineer/designer hours of work.

In the last 50 years of the twentieth century, several methods were introduced and implemented for improving the design process for minimizing times and costs. An enormous scientific/generational jump has been introduced by the advent of digital era.

The digital era change radically the concept of prototype in design process.

The use of both mathematical and engineering models in engineering design allows designers to speed up the design process and to improve and optimise their results from different perspectives. The use of models that describe the 'behaviour' of a product (artefact) in terms of a human-artefact interface (HAI) can help designers include HCD optimisation as a step in the design cycle. The design cycle can be summarised by the following diagram [24] in Fig. 1.3:

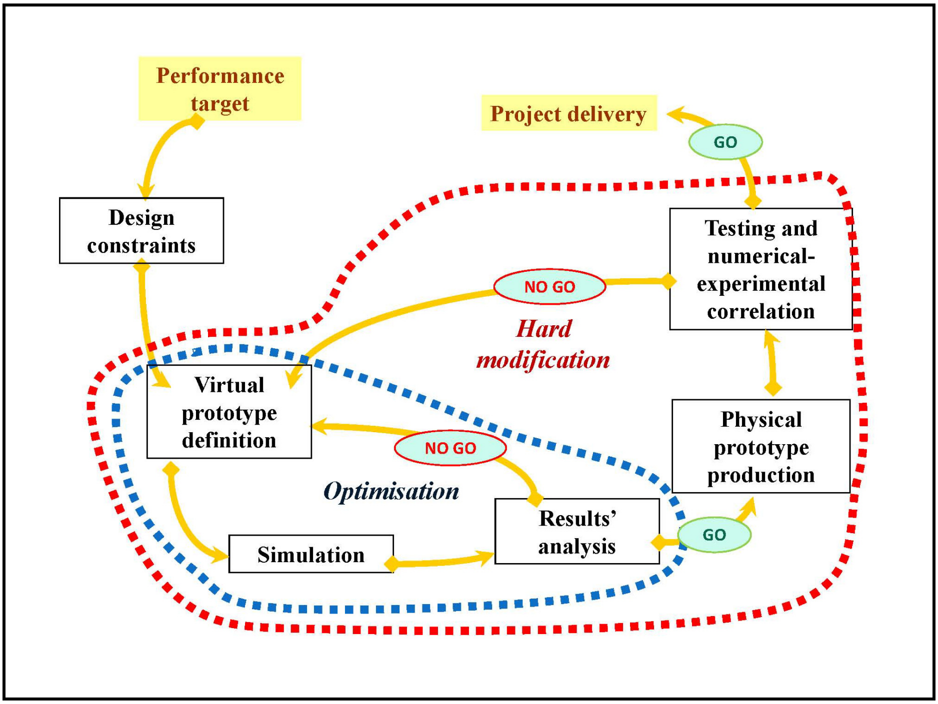

Fig. 1.3: Product design and development diagram in digital era

In this process, target setting generally begins with customer needs and the functional requirements of the final artefact. When introducing

HCD to the artefact development plan, we require models that describe the HAI in the very early phase of the design. Contrarily, (dis)comfort performances can be discovered and evaluated only after the production of a physical prototype. Due to the subjectivity of comfort perception, it is difficult to objectivise this kind of performance via a model [25], and integrating these models into the artefact development plan is even more challenging. To achieve this requires the integration of the standard or non-standard design methods and the techniques for modelling the (dis)comfort behaviour. Simply stated, ideally we have a comfort-driven design method that can be applied to the early phase of the design process, in the digital phase and in the prototype phase and that can help designers and engineers optimise the product by introducing comfort-related issues in the target-setting phase.

1.3 Virtual Prototyping and Comfort prediction

VP (Virtual Prototyping) techniques and their development and diffusion in industrial environments make it possible, since 90's, to design and redesign products, processes and work-places in virtual environment; These kinds of technologies have deeply changed the design and the development process both for product design and for process design. The main add-on that these technologies give to designers is the possibility to analyse and test the product/process performances before realizing the physical prototypes. This design approach (VP) allows, to optimize the product under different points of view and to shorten the time to market, avoiding the worst mistakes and the foreseeing the product/process behaviour.

DHM (Digital Human Modelling) techniques can be cited[2] as the latest ones that have been introduced in the recent past and allow to virtually evaluate, in specified aspects and environments, the interaction between humans and the main commands/hand tools of machine/workplace. The development of these DHMs has been done contemporarily with the development of ergonomics and comfort evaluation models because the main target for companies and researchers was and is the capability to make the preventive evaluation of Human

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[2] This statement can be easily demonstrated through the navigation into the world of conferences, papers and software technologies that are daily developed and proposed to designers.

Machine Interfaces (HMI) both in terms of comfort/ergonomics while processing a product than in terms of comfort/ergonomics while using the product.

A short History of these methods might be useful: since the '70 years many studies were addressed to the biomechanical models development. The first notable results were achieved by Chow and Jacobson [26] (1971), which developed a theory for the human movements optimal control; Seireg and Arvikar [27] (1975), whose results were taken by Rohrle [28] (1984), studied the optimal distribution problem of the muscular strength in the hip, knee and ankle articulations during the walking; Bean, Chaffin and Schultz [29] (1988) proposed a linear programming method for the muscular strengths computation in a muscular-skeletal system.

In the last years, the work of thousands of researchers allow to develop DHM (Digital Human Modelling) software provided with digital biomechanical models, like, for instance, Jack (UGS), Ramsis (TechMat) Delmia (Dassault Systemes) and AnyBody (Anybody Technology); most of them allow to simulate human movements and interactions by specific tools.

Nevertheless, if the ergonomic studies reached a very good level of affordability through the development of several qualitative and quantitative methods (see next paragraph), the implementation of methods to objectively evaluate the (dis)comfort behaviour of humans is far from being completely developed.

Remembering that a complex (dis)comfort experience is always due to the interactions of several subjective contributes and noise effects, the target of “understanding the “objective” behaviour of humans” seems to be an **oxymoron.**

Thus, the ***third research question*** of this work is: “Is it possible to develop a method to more objectively evaluate the (dis)comfort experience of humans?”

1.4 State of the art of HMI evaluation

Ergonomics and comfort in design development began with HCD/UCD, as the first requirements of human-machine interface (HMI) design are the basis of good safety levels, reducing the risk of health problems such as muscular-skeletal disease in users. During the last two decades, the market has been impacted by several agreements on guidelines and laws that work both as new constraints and as new challenges for designers:

- EN ISO (International Organization for Standardization) 14738, September 2002 “Safety of machinery – anthropometric requirements for the design of workstations at machinery” [30];
- ISO 11226/2000 – “Ergonomics – evaluation of static working posture” [31];
- EN 1005-3/2009 “Safety of machinery – human physical performance – part 3: recommended force limits for machinery operation” [32].

ISO 11228 [33] was the first ISO Standard that gave us a good reference on ergonomics evaluation mainly based on a “Postural Load Index” that represents the Ergonomics level of examined posture [34,35], even if does not give us information about the perceived well-being. ISO 11228-3 deals with evaluation of risk in cases that require repetitive movements. Risk evaluation is based on two procedures: first, an initial screening of the check list proposed by ISO Standards; second, a detailed evaluation procedure based on International standard methods of Ergonomic analysis like RULA [36], REBA [37], LUBA [38], STRAIN INDEX [39]; OCRA [40], OREGE [41], NIOSH [42-44] and others, with a preference given to the OCRA [34,35] due to its easiness and to the integrated tools available in the most widespread DHM software. In the first decade of 2000, these methods have been widely used to check and verify the existing workplaces and HMI in order to propose an ergonomic driven re-design of them. The literature contains many papers addressing ergonomics. Nevertheless, ergonomics concepts are frequently developed and used in relation to a specific product or process. Few papers present a systematic approach to product/process/interaction design under the rubric of ergonomic-driven design. In Caputo et al. [45], ergonomics was applied to car-interior design using augmented reality devices; in Bordegoni et al [46], VR haptic devices were used to perform ergonomic analyses in two cases of ergonomic-driven design; in Di Gironimo et al [47], the Kano model was used to formulate an ergonomics-driven design method; while in Di Gironimo et al [48], a Virtual OWAS/RULA analysis was performed to re-design the cabin cockpit of a train in a completely digital environment.

In the second part of the first decade, we begin to find papers dealing with the application of ergonomic principles for designing products, processes, workplaces and other general interactions between humans and artefacts. Nevertheless, the standard methods currently available are not able to identify and quantify the necessary parameters to perform a comfort analysis, also because the wellbeing of users/humans is a very ‘slim’ subrange of the ergonomic safety-range in the HMI domain.

Looking back over the last 30 years, there are many papers dealing with (dis)comfort and general well-being in the literature (see tab.1 in [49]. The majority have tried to demonstrate and quantify the relationship between environmental and physiological factors and perceived comfort (Galinsky et al., 2000 [50]; Hamberg-van Reenen et al., 2008 [17]; Naddeo and Memoli, 2009 [51]). Papers that explicitly address the concept of comfort are those by Helander and Zhang (1997) [52], De Looze et al. (2003) [25], Moes (2005) [53], Kuijt-Evers et al. (2004) [54] and Hiemstra-van Mastrigt et al. (2017) [55]. However, most of the others concern the relationship between subjective perception of comfort/discomfort and factors relating to the product/process/interaction/environment/users. Many papers focus on a specific interaction between humans and artefacts (HAI) in order to understand the mechanism of (dis)comfort perception and identify the artefacts’ parameters that influence that perception. A search for papers whose keywords (and abstracts) contain “Comfort”AND“Design” or “Discomfort”AND”Design” in the main scientific databases reveals several papers written in the last 20 years. In Taptagaporn et al. [56] and Sisay et al [57], a VDT workstation was designed using guidelines based on the physiological resting states of the eye, and on postural analysis; Lai et al. [58], address perceived comfort due to lateral acceleration in motorcycle design; in Wijaya et al. [59], Menegon et al. [60] and Yang et al. [61], derive guidelines for designing new comfortable seats from experiments concerning vibration perception; Corradi et al. [62], Hasan [63], Nejlaoui et al. [64] and Li et al. [65] give proposals for estimating the comfort indexes of a rail vehicle at the design stage based on lateral acceleration; Dainoff et al. [66] present a design approach based on ecological comfort/ergonomics; Vlaovic et al. [67] give the results of subjective comfort analysis for new materials for chairs; Albers et al. [68] adopt a systematic approach to train design using tools for human comfort; Allocca et al. [69] present a noise-comfort approach for regional aircraft design; Webster et al. [70] provide a study of cricket leg guard comfort by incorporating subjective end-user perceptions in the design process; Chen et al. [71] and Mohamad et al. [72] take comfort as one of their design targets in seat design; Sharma et al. [73] and Xiang-Rong et al. [74] link subjects' comfort to their behaviour in a crowd; Shen et al. [75] and Tan et al. [76] relate thermal comfort during sleep to mattress characteristics; Pei et al. [77] and Wang et al. [78] relate environmental comfort to the controlled air quality perceived by subjects; and Vink et al. [79] define some seat adjustability guidelines by examining the differences in pressure sensitivity for areas of the human body in contact with the seat pan and backrest of a vehicle seat.

The main purpose of these papers is to produce guidelines for designers seeking to create more comfortable products and drive their development and innovation. The problem of defining a comfort-driven design method has been explicitly addressed by several papers. For example, Pandharipande et al. [80] examine the user-comfort-driven design of indoor LED lighting control systems via spatial illumination rendering; Vallone et al. [81] propose the redesign of a manufacturing plant's workstation to improve operators' perceived comfort. Each of these authors seeks to extrapolate or synthetize a general rule for assessing a comfort evaluation and, ultimately, to provide initial guidelines for a comfort-driven design method.

1.5 *Comfort and Discomfort models*

The need of a more suitable and complete comfort model, shown in Fig. 1.5, has come in the second decade of the 2000 and was highlighted in the work of Vink and Hallbeck (2012)[82]. In this work an exhaustive analysis of the state of the art about the comfort in HMI has been performed by authors and starting from Helander (2003)[83], through the Moes' (2005)[53] model represented in Fig. 1.4.

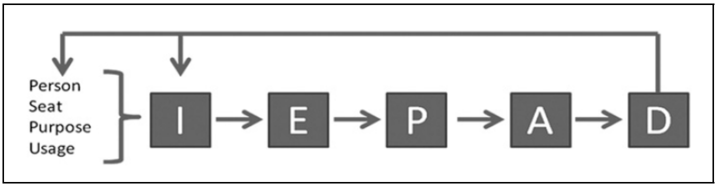


Fig. 1.4: Moes model of discomfort perception

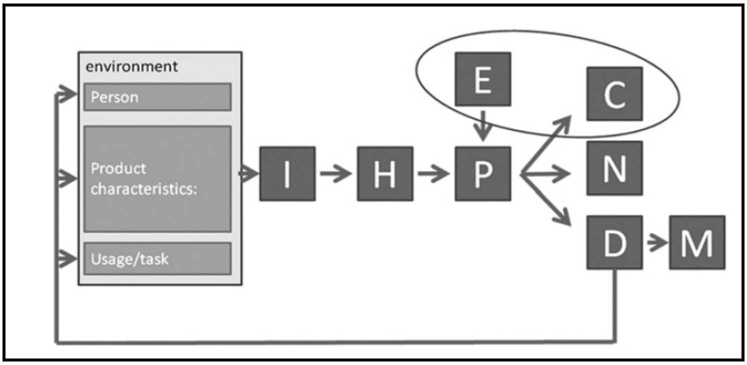


Fig. 1.5: Vink-Hallbeck model of comfort/discomfort perception

They start from the following main topics individuated in a wide literature overview, for introducing their model:

1) Sensory input (De Korte et al.[84], 2012; Vink et al., 2012[82]);
2) Activities conducted during the measurement with an influence on comfort (Groenesteijn et al., 2012[85]; Ellegast et al., 2012[86]);
3) Different bodily regions (Franz et al., 2012[87]; Kong et al., 2012[88]);
4) Effect of the product' contour on comfort (Kamp, 2012[89]; Naddeo et al. 2010[35]; Noro et al., 2012[90]);
5) Physical loading (Borg, 1982[91]; Lee et al., 2012[92], Di Pardo et al. 2008[93]; Zenk et al., 2012[94]).

Moes (2005) [53] deals about a specific case on the topic of "seat-design" and describes that if a person uses a seat with a specific purpose, the interaction (I) arises. For example, this interaction can consist of the pressure distribution of the contact area between the subject and seat. An interaction results in internal body effects (E), such as tissue deformation or the compression of nerves and blood vessels. These effects can be perceived (P) and interpreted, for instance as pain. The next phase is the appreciation (A) of the perception. If these factors are not appreciated, it can lead to feelings of discomfort (D) and, in order to improve the experience, you need to work on the interaction or to set a different environment by acting on factors in it.

Vink and Hallbeck (2012) [82] have modified this model (Fig. 1.5); in their opinion, the interaction (I) with an environment is caused by the contact (could also be a non-physical contact, like a signal in the study of De Korte et al. [84]) between the human and the product and its usage.

This can result in internal human body effects (H), such as tactile sensations, body posture change and muscle activation. The perceived effects (P) are influenced by the human body effects, but also by expectations (E). These are interpreted as comfortable (C), you feel nothing (N), or it can lead to feelings of discomfort (D) and the Discomfort could result in musculoskeletal complaints (M).

In 2014 Naddeo et al. [95] proposed the following model in Fig. 1.6:

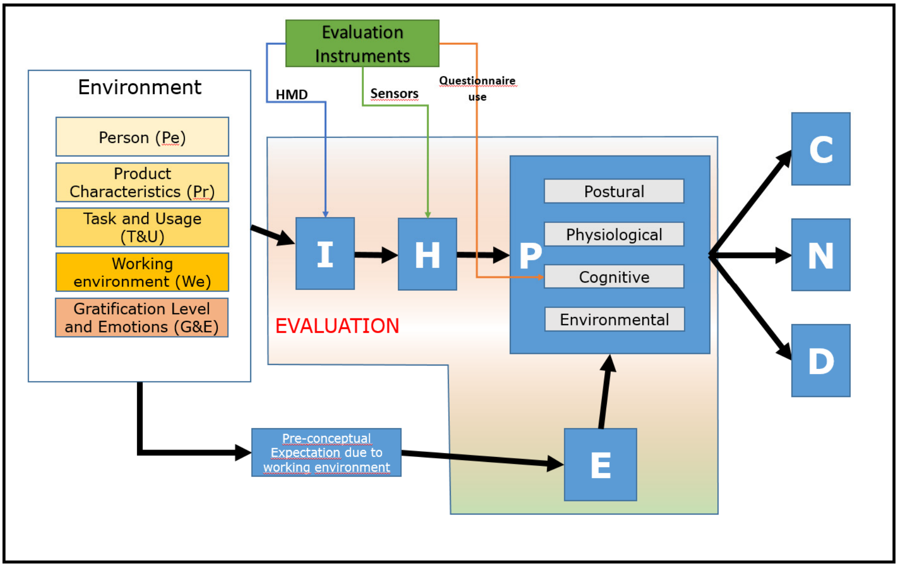


Fig. 1.6: New proposal for comfort perception model

In this model, the Environment is represented by the logic sum of five main aspects that contribute to HMI description and classification:

- Person (Pe): represent the whole body geometric and personal characteristics of human involved in tasks;
- Product (Pr): represent all geometric and non-geometric characteristics that describe the element that come in contact with the human body during task execution (shape, materials, colour, surfaces' treatment and so on…);
- Task/Usage (T&U): represent all the task or the use that humans can do during HMI experience (kind of contact, timing, kind of interaction);
- Working environment (We): represent the set of parameters that characterizes the working environment (it means also where the activity takes place), both under climate and under layout point of

view (temperature, humidity, lighting, working seat, kind of workspace);
- Satisfaction/Gratification level and emotions (G&E): represent the set of work characteristics and the emotional state that contribute to the satisfaction/dissatisfaction of worker (job position in organization chart, working shifts, gratification, salary and so on) and is widely related to the general environment.

The Vink/Hallbeck model (2012) [82] is integrated with a relation that directly connects the Environment in which the comfort/discomfort is experienced with the expectation through the coding of several pre-conceptual aspects due to not only the same environment but also to the cultural/experience background of the worker. An aspect that cannot be underestimated because it is always present when a comfort/discomfort evaluation is performed also integrates this model: the perception modification due to experimental devices needed to evaluate comfort. These “devices” can modify most of contributes to the formation of the comfort/discomfort perception.

For example, a HMD (Head mounted display) used for VR (Virtual Reality) application in HMI evaluation can modify the Postural Comfort Perception (Interaction – I); the use of markers/sensors on the naked body to perform pressure/temperature/movement data acquisition can change the Physiological Comfort Perception (Human Body effect – H); the use of questionnaire can annoy the workers and directly modify his Cognitive Comfort perception (Perceived effects – P).

In 2014, Vink et al. [96] the model of discomfort takes into account more generically the interaction between Humans and Artefacts into a generic environment (see Fig. 1.7 below), widening the concept of Human-Machine Interaction:

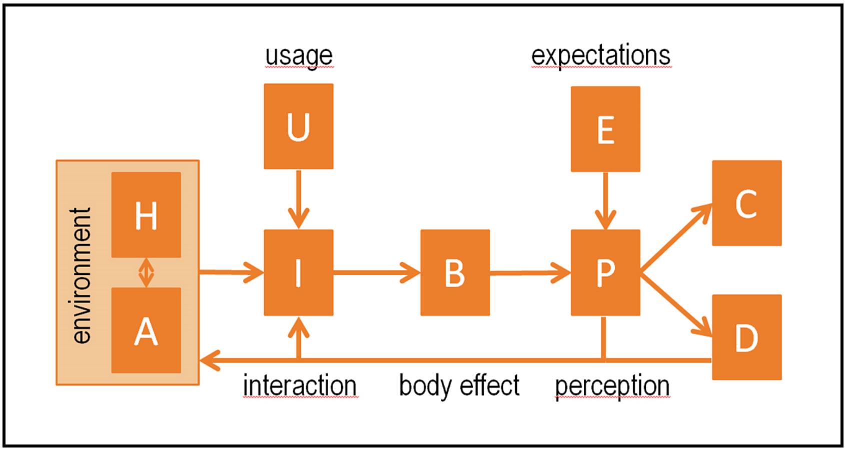


Fig. 1.7: Vink 2014 comfort model

In this model, the Artefact (A) and Human (H) are in an environment. Usage (U) causes an Interaction (I) between the person and product, which causes human Body effects (B). Then it will be Perceived (P) in the human brain, which is influenced by Expectations (E) and could give a certain Comfort (C) and Discomfort (D). The effect of comfort/discomfort can affect directly how humans perceive the environment and, so, the Comfort/Discomfort experience has an evolution in time.

This model is completely overlapped with the NC-model.

It is quite difficult to find other general models for (dis)comfort perceptions that are explained or expressed by a mathematical/logical formulation. However, several other comfort models have been proposed in different terms in recent decades. Most of these addresses a specific, context-related issue. Many papers have been written about thermal comfort [97], and these generally adopt human thermal models (e.g. the Fanger model) to describe perceptions of comfort/discomfort. All the other aspects are addressed in the following papers:

Looking for “Comfort”AND”Model” in the main scientific databases, the following papers deal with Comfort models. In [82], [95], [98] and [99], a conceptual model of Comfort perception that takes into account physical, psychological, object, context and environment have been presented.

In [100], a comfort index for seat has been modelled through Artificial Neural Networks (ANN) and Step-wise Linear Regression (SLR) on several heterogeneous data. In [101] the driving posture comfort is modelled through a function obtained by Support Vector Machine (SVM) regression analysis methods and in [102] a Multiple Linear Regression (MLR) is used for fusing subjective and objective information.

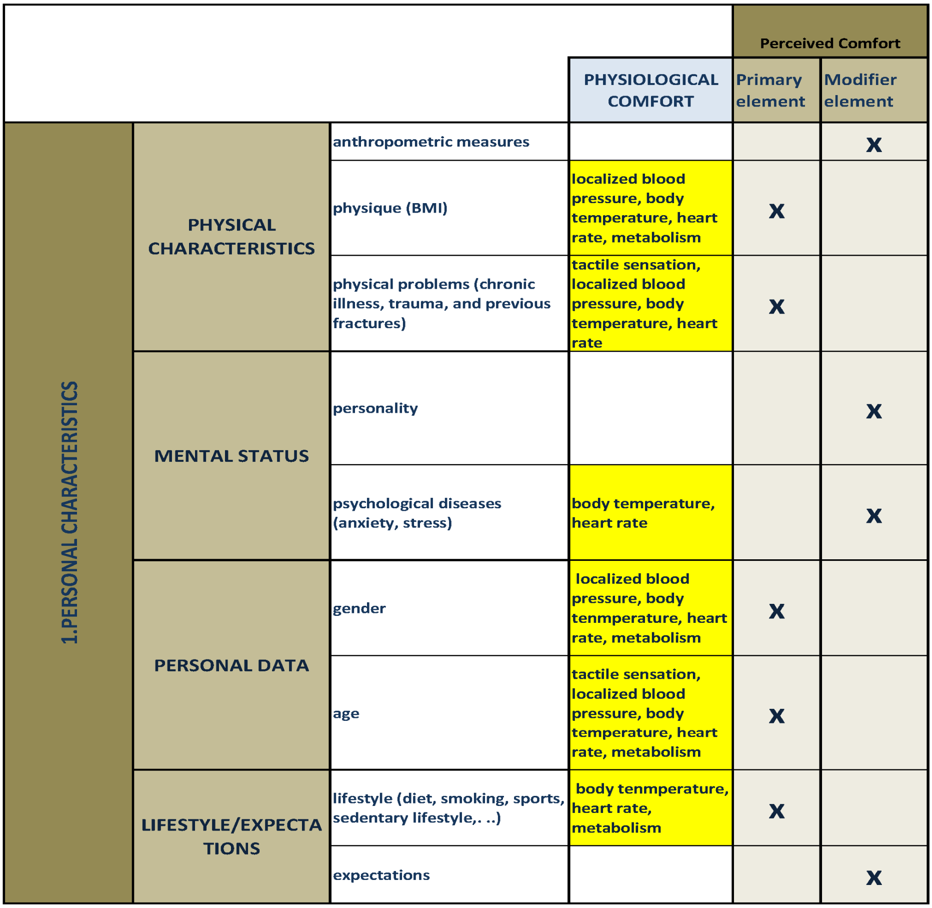
In [98], [103], [104], [105], [106], [107] and [108], an algorithmic approach is used for optimizing a comfort function based on simulations' results. In [109], a Nested Logit Model is developed for predicting Subway system comfort. In [110] a Genetic Algorithm is used for describing the postural comfort related to the Human joints' position. In [111], Fuzzy Key Means (FKM) is used for defining a comfort model for sleep comfort, while in [112], [113] and in [114] a Sugeno Fuzzy inference system is used for defining a comfort model for car passengers and for products. In [115], Machine Learning techniques have been used for developing a predictive comfort model for HVAC. In [116], a Multilayered Model Based on Situated Multi-agent Systems has been developed for assessing people comfort into a crowd. In [117] a Probabilistic model for human comfort is presented.

Looking for "Discomfort"AND"Model" in the main scientific databases (like Scopus, ISI-WOS and Scholar), the following papers seal with Discomfort models.

In [104], [118], [119] and [120], an algorithmic approach is used fusing subjective and objective information in order to obtain a predictive discomfort function. In [121] a Multiple Linear Regression (MLR) is used for fusing subjective and objective information about perceived discomfort. In [122], [123], [124], [125], [126] and [127], a predictive postural discomfort model has been developed through experimental function's extrapolation and fusion. In [128], [129] and [130] a database modelling approach is used to describe the discomfort related to a position.

1.6 Comfort contributes fusion rule

The Vink-Hallbeck framework, as modified by Naddeo and Cappetti (NC-Model of perception), is able to synthetize the concept through which we explain that comfort and discomfort are the measure of the degree of appreciation linked to expectation and due to the perception of the interaction level (I) between person (H) and Environment (Env).



				Perceived Comfort	
			PHYSIOLOGICAL COMFORT	Primary element	Modifier element
1.PERSONAL CHARACTERISTICS	PHYSICAL CHARACTERISTICS	anthropometric measures			X
		physique (BMI)	localized blood pressure, body temperature, heart rate, metabolism	X	
		physical problems (chronic illness, trauma, and previous fractures)	tactile sensation, localized blood pressure, body temperature, heart rate	X	
	MENTAL STATUS	personality			X
		psychological diseases (anxiety, stress)	body temperature, heart rate		X
	PERSONAL DATA	gender	localized blood pressure, body tenmperature, heart rate, metabolism	X	
		age	tactile sensation, localized blood pressure, body temperature, heart rate, metabolism	X	
	LIFESTYLE/EXPECTATIONS	lifestyle (diet, smoking, sports, sedentary lifestyle,. ..)	body tenmperature, heart rate, metabolism	X	
		expectations			X

Fig. 1.8: Comfort-framework for Personal Characteristics (left)

	Perceived Comfort			Perceived Comfort			Perceived Comfort	
EMOTIONAL-COGNITIVE COMFORT	Primary element	Modifier element	ORGANIZATIONAL-ENVIROMENTAL COMFORT	Primary element	Modifier element	POSTURAL COMFORT	Primary element	Modifier element
		X				posture overload, muscle complaint	X	
level of perceived tiredness		X				muscle effort, posture overload, muscle complaint	X	
work overload, level of perceived tiredness		X				muscle effort, posture overload, muscle complaint	X	
work overload,level of perceived safety, aggressiveness and irritability, level of perceived tiredness, stress, lack of attention	X							X
level of perceived safety, aggressiveness and irritability, level of perceived tiredness, stress, lack of attention	X							X
	X						X	
lack of attention	X					muscle effort	X	
aggressiveness and irritability, lack of attention		X				muscle effort		X
level of perceived safety, aggressiveness and irritability, stress	X							X

Fig. 1.8: Comfort-framework for Personal Characteristics (right)

The work starts from the definition of the wider number of elements that can be linked to Environment's aspect and their classification through two main axioms:

The first axiom asserts that "Each element involved in HMI experience can contribute to one or more kinds among four types of comfort[3]: Postural, Cognitive, Physiologic and Environmental, see Naddeo, 2013[95]. An example of what is claimed can be found in the following figures in which the "comfort perception formation" and its possible causes are represented (fig. 1.9) and the influence on comfort[4] and on body effects of personal characteristics (Pe) of the user/person is analysed and explained (fig. 1.8).

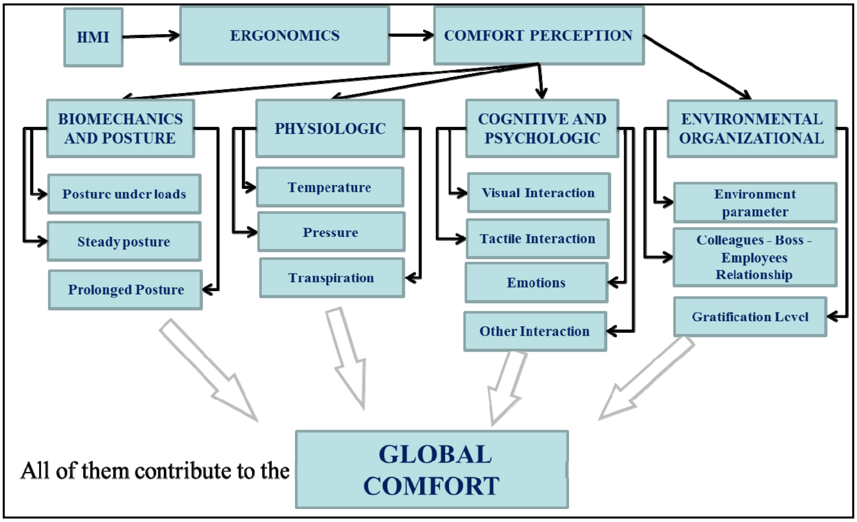


Fig. 1.9: Main causes of Global Comfort perception

This macro-schematization of comfort/discomfort experience (global/overall pereceived discomfort) allows individuating most of the elements that contributes to comfort/discomfort experience and to classify them in terms of Human body effects related to four types of comfort (Ci)/discomfort (Di) perception.

The second axiom asserts that "Each element involved in HMI experience can be classified as a primary element or as modifier element":

---

[3] The split of comfort perception in four types of comfort have been hypotesized by Naddeo et. al in 2014[95].

[4] The empty spaces in the table/matrix mean that the specific charachteristic is not related to the type of comfort.

a primary element is defined as an element that directly contributes to the formation of the comfort/discomfort perception (such as anthropometric measures for the postural Comfort); a modifier element is defined as an element that can modify a previously formed perception (such as time of sitting in physiologic Comfort).

The primary elements are the ones that weigh on the real interaction ability of a person while the secondary elements (modifier) weigh on the perception ability and are related to person and environment characteristics. The expectation acts on a person and can sensibly influence the level of threshold between comfort and discomfort.

Thanks to the axioms and the NC-Model, Comfort (C) and Discomfort (D) can be represented by these formulas:

$$\begin{aligned} C_i &= Mod_C * P_C(h(Pe, Pr, T\&U, We, G\&E) - E \\ D_i &= Mod_D * P_D(h(Pe, Pr, T\&U, We, G\&E) + E \end{aligned} \quad (1)$$

In which:

- **Mod** = Modifier of **P** (Perception) of the **h** = Human body effect due to:
- ***Pe*** = Personal characteristics
- ***Pr*** = Product characteristics
- ***T&U*** = Task and usage
- ***We*** = Working environment (environment where activity is performed)
- ***G&E*** = Gratification level and emotions
- ***E*** = Expectations

Taking a look at the (dis)comfort models analysed and found in the literature (see the previous paragraph), all of them may be seen as a part of the general model expressed in the above formula by Naddeo et al. [95] However, this formula has no possibility to be used, as it requires that the function describing the relationship between a factor influencing (dis)comfort perception and the perception itself is deployed. This is a challenge that scientists must face when implementing a model that allows them to perform a preventive analysis of (dis)comfort in the virtual design process.

Thus, the ***fourth research question*** of this thesis is: “What is the right research approach to define functions in the (dis)comfort equation?”

1.7 A general framework for (dis)comfort coding

In [95] and [131], the NC-Model has been deployed and detailed. For each kind of interaction (I), one or more human body effects (H) have been found through a wide research within the ergonomic/comfort bibliography. The research work looked for the most important factors that are related to the comfort and discomfort aspects; they were classified through an inductive method. The main step is codifying and understanding the domain in which we have to define the comfort/discomfort perception. The comfort domain can be defined as the whole experience that gives the human a degree/level of positive perceiving and this level can be affected both by external experiences and by human intrinsic characteristics.

In the working environment (it means, as explained before, the environment in which the activity takes place), human's experience consists of the human body that reacts while doing an activity (task/usage) using products and perceiving (P) an effect.

The previously described "classes" of factors, Pe, Pr, T&U, We and G&E, contribute to this HMI experience The purpose of the proposed framework is to explain the connections among the interactions (I) with human body effects (H), in order to evaluate if and how these effects are perceived (P) and if and how they affect the four identified types of comfort/discomfort perception: postural, cognitive, environmental and physiological.

All data have been organized in a comfort-matrix that is divided in five sections represented in Figures 1.8, 1.10, 1.11, 1.12 and 1.13. Most of matrix rows have been defined by findings described in the literature.

The first class of factors is related to the human characteristics i.e. physical characteristics, mental state, personal data, lifestyle and expectations. There is literature indicating that human characteristics influence physiological, cognitive and postural comfort while there is not a correlation between human characteristics and the quality of the environment. Each subclass of human characteristics has been deployed in order to consider it in all own aspects. Particularly, the physical characteristics are related to anthropometric measures [132], physique and physical problems/disease. The mental state takes into account the human personality type [133] and the psychological diseases. The personal data are related to age and gender. In the matrix, it has been also considered the lifestyle such as sport playing, eating habits and personal expectations.

The second class of factors is related to the work/task characteristics. If the comfort is the result of the interaction between man and the activity that he does, it is not possible not to consider the activity characteristics and the environmental characteristics. These factors concern aspects related to the work-station/seat characteristics, the type of activity and the objects' element with which the user interactsfor the task's execution. For the workstation/seat or product used, both the posture the human has to take in order to do the task and the kind of individual safety equipment have been considered. Both aspects affect the comfort perception: for example, in Alessandro Apostolico et al. [89], it has been demonstrated that posture configuration can strongly influence the level of comfort perceived. Also the type of task/usage that man has to do affects the comfort perception. Because of the comfort-matrix has to be applied for any type of work/activity, we have listed the key features that define a generic work/activity and influence the perceived comfort. Some aspects that we have considered are: level of precision required [134], time maintaining the posture [38] and work shifts [135]. The last aspect is related to the objects/tools that are used for the task's execution. It has been demonstrated that the shapes of the objects [54] or their careful positioning in the workspace [136] can facilitate the user to execute the task. The result can be an increase of the level of comfort.

The third class of factors that has to be considered is related to the characteristics of the environment. If we consider that a person has to stay in a specific place for several hours, we have to consider that a pleasant[5] environment may significantly affect the person's well-being. The environment is composed of: visual, olfactory, acoustic and thermal well-being, wellbeing associated to the workspace and wellbeing associated to the state of maintenance of the environment. The visual comfort is related both to the conditions of lighting inside the environment and to the colors used. For example in Szczepanska-Rosiak [137], the evaluation of the visual comfort is influenced by the lighting conditions, both the artificial and the natural one, the workspace colours and the effects of light-reflection on the walls.

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[5] Pleasant means: "giving a sense of happy satisfaction or enjoyment".

				Perceived Comfort			Perceived Comfort	
			PHYSIOLOGICAL COMFORT	Primary element	Modifier element	EMOTIONAL-COGNITIVE COMFORT	Primary element	Modifier element
2.WORK/TASK CHARACTERISTICS	WORKSTATION	posture: angles and joints			x			x
		individual safety equipment: overall dimensions and heaviness	tactile sensation, localized blood pressure, body temperature		x	level of perceived safety, lack of attention		x
	WORK ACTIVITY & TASK	type of loads and actuation (lifting, pulling, pushing)	localized blood pressure, body temperature, heart rate		x	level of perceived tiredness		x
		oparating speed	body temperature		x	work overload,level of perceived tiredness, stress		x
		actions' frequency	body temperature		x	work overload, level of perceived tiredness, stress		x
		rest-pause duration and frequency			x	work overload, level of perceived safety, aggressiveness and irritability, level of perceived tiredness, stress, lack of attention		x
		level of precision			x	aggressiveness and irritability, level of perceived tiredness, stress, lack of attention		x
		time maintaining of the posture with and/or without loads	localized blood pressure, body temperature, heart rate		x	aggressiveness and irritability, level of perceived tiredness		x
		time and duration of work activity/tasks			x	work overload,aggressiveness and irritability, level of perceived tiredness, stress, lack of attention		x
		work-shifts	muskular exertion, aggressiveness, nervousness, tiredness		x	work overload, level of perceived safety, aggressiveness and irritability, level of perceived tiredness, lack of attention		x
	CHARACTERISTICS OF TOOLS/OBJECTS WITH WHICH A PERSON INTERACTS	shape			x			x
		weight			x			x
		relative position between person and object/tool			x			x
		frequency of lifting / pulling / pushing	heart rate, localized blood pressure, body temperature		x	level of perceived tiredness	x	
		handling characteristics (grip, grasp, pinch, ...)			x			x
		customization of the workstation (sitting)	tactile sensation		x	level of perceived tiredness		x
		commands' layout			x			x

Fig. 1.10: Comfort-framework for Work/Task Characteristics (left)

	Perceived Comfort			Perceived Comfort	
ORGANIZATIONAL-ENVIROMENTAL COMFORT	Primary element	Modifier element	POSTURAL COMFORT	Primary element	Modifier element
		x	muscle effort, posture overload, muscle complaint	x	
		x	muscle effort, posture overload, muscle complaint		x
		x	muscle effort, posture overload, muscle complaint	x	
	x		muscle effort, posture overload, muscle complaint		x
	x		muscle effort, posture overload, muscle complaint		x
	x		muscle effort, posture overload, muscle complaint		x
	x		muscle effort, posture overload, muscle complaint		x
		x	muscle effort, posture overload, muscle complaint	x	
	x		muscle effort, posture overload, muscle complaint		x
level of perceived safety	x				x
		x	muscle effort, posture overload, muscle complaint	x	
level of perceived safety		x	muscle effort, posture overload, muscle complaint	x	
level of perceived safety		x	muscle effort, posture overload, muscle complaint	x	
		x	muscle effort, posture overload, muscle complaint		x
		x	muscle effort, posture overload, muscle complaint	x	
level of perceived safety		x	muscle effort, posture overload, muscle complaint	x	
			muscle effort, posture overload, muscle complaint	x	

Fig. 1.10: Comfort-framework for Work/Task Characteristics (right part)

				Perceived Comfort			Perceived Comfort	
			PHYSIOLOGICAL COMFORT	Primary element	Modifier element	EMOTIONAL-COGNITIVE COMFORT	Primary element	Modifier element
3.WORKING ENVIRONMENTS' CHARACTERISTICS	VISUAL WELL-BEING	colors			x	aggressiveness and irritability, level of perceived tiredness, lack of attention		x
		artificial lightinging conditions			x	level of perceived safety, aggressiveness and irritability,level of perceived tiredness		x
		natural lighting conditions			x	aggressiveness and irritability, level of perceived tiredness		x
		lights' reflection and refraction on walls and objects			x	aggressiveness and irritability, level of perceived tiredness, lack of attention		x
	OLFACTORY WELL-BEING	air quality	aggressiveness, nervousness		x	aggressiveness and irritability		x
		odors			x	aggressiveness and irritability, lack of attention		x
	AUDITIVE WELL-BEING	noises			x	level of perceived safety, aggressiveness and irritability, level of perceived tiredness, lack of attention		x
		vibrations			x	work overload, level of perceived safety, aggressiveness and irritability, level of perceived tiredness, lack of attention		x
	SPACES	workspace	muskular exertion, aggressiveness, nervousness		x	level of perceived safety, aggressiveness and irritability		x
		plant-layout			x			x
		condition and inclination of the floor (only in the case of the standing posture)			x			x
	ENVIROMENT CHARACTERISTICS	cleanliness			x	aggressiveness and irritability		x
		tidiness			x	work overload, aggressiveness and irritability		x
	THERMAL WELL-BEING	air-temperature	body temperature, aggressiveness and nervousness		x	aggressiveness and irritability, lack of attention		x
		interface temperature	tactile sensation, localized blood pressure, body temperature	x		lack of attention		x
		humidity	localized blood pressure		x			x
		thermal resistance of clothing	tactile sensation, localized blood pressure, body temperature	x				x
		persistence in a thermal condition	tactile sensation, localized blood pressure, body temperature, aggressiveness, nervousness	x		aggressiveness and irritability, lack of attention		x
		contact pressure	tactile sensation, localized blood pressure	x				x
		air speed	body temperature		x			x

Fig. 1.11: Comfort-framework for Working Environment Characteristics (left part)

	Perceived Comfort			Perceived Comfort	
ORGANIZATIONAL-ENVIROMENTAL COMFORT	Primary element	Modifier element	POSTURAL COMFORT	Primary element	Modifier element
	x				x
level of perceived safety	x		muscle complaint		x
	x		muscle complaint		x
	x		muscle complaint		x
	x				x
	x				x
level of perceived safety	x				x
	x		muscle effort, posture overload, muscle complaint	x	
level of perceived safety	x		muscle effort, posture overload, muscle complaint		x
level of perceived safety	x				x
level of perceived safety	x		muscle effort, posture overload, muscle complaint		x
	x				x
	x				x
level of perceived safety	x				x
		x			x
	x				x
		x			x
level of perceived safety		x			x
		x			x
	x				x

Fig. 1.11: Comfort-framework for Working Environment Characteristics (right part)

The perceived comfort is associated also to the worker's satisfaction for the air quality. In addition, the indoor air quality and the odours have to be considered as elements that can affect the whole comfort perception. Noises and vibrations have been considered when talking about the acoustic wellbeing: unwanted noises and vibrations, in fact, are huge distractions and can cause stress conditions in the workplace [138].

Another aspect that influences the worker's (dis)comfort is the thermal condition; in [139], for example, the thermal aspect is treated as the consequence of influence of factors humidity, temperature and thermal-resistance of the clothes (in terms of conduction, convection radiation). The last two aspects we found in literature are the space, interpreted both as workspace in [140] and as plant/office layout, and the state of maintenance of the environment. If the worker is obliged to work in a small area, to do forced movements and to stay in a dirty or in a messy place his level of comfort strongly decreases [140].

The last class of factors that has to be considered is related to the degree of satisfaction and emotions. A job, or in general an activity, can be more or less satisfying in relation both to the content and to the context of the work. The content of the work includes several factors i.e. the level of recognition, the direct responsibility of the work and the possibility to learn [141]. A work can have a degree of content too high or too low and it can be the cause of the absence of incentive and the decrease of the level of comfort. In the context of the work, for example, the relationships with the colleagues and managers or the rigidity of the norms and procedures have been considered [142,143].

The interaction that the individual has with these classes of factors causes effects on worker (or occupant, or tool-user) and contributes to the development of a comfort perception. The effects are different for each type of comfort among postural, cognitive, physiological and environmental factors. The comfort matrix is an attempt to explain and deploy each kind of class and describe the relationships among causes (Interactions) and effects (Body effects) for each kind of perceived comfort. Some examples of reading the matrix are explained in the Figures 1.8, 1.10, 1.11, 1.12 and 1.13.

				Perceived Comfort			Perceived Comfort			Perceived Comfort			Perceived Comfort	
			PHYSIOLOGICAL COMFORT	Primary element	Modifier element	EMOTIONAL-COGNITIVE COMFORT	Primary element	Modifier element	ORGANIZATIONAL-ENVIROMENTAL COMFORT	Primary element	Modifier element	POSTURAL COMFORT	Primary element	Modifier element
4. LEVEL OF GRATIFICATION	GRATIFICATION LINKED TO THE CONTENT OF WORK	rewards and money-grants			x	aggressiveness and irritability, stress	x				x			x
		direct work responsibilities			x	work overload, aggressiveness and irritability, level of perceived tiredness, stress	x				x			x
		growth opportunities			x	aggressiveness and irritability	x				x			x
	ORGANIZATION/ ENVIRONMENT	collaboration with colleagues			x	aggressiveness and irritability, stress	x				x			x
		rigidity of the regulations and procedures			x	level of perceived safety, aggressiveness and irritability, stress	x				x			x
		relationship with managements			x	aggressiveness and irritability, stress	x				x			x
		attractiveness of the environments and furniture			x	aggressiveness and irritability	x				x			x
		level of tiredness	muskular exertion, aggressiveness, nervousness, tiredness		x	work overload, aggressiveness and irritability, level of perceived tiredness, stress, lack of attention	x				x			x

Fig. 1.12: Comfort-framework for Level of Gratification

			Perceived Comfort			Perceived Comfort			Perceived Comfort			Perceived Comfort	
		PHYSIOLOGICAL COMFORT	Primary element	Modifier element	EMOTIONAL-COGNITIVE COMFORT	Primary element	Modifier element	ORGANIZATIONAL-ENVIROMENTAL COMFORT	Primary element	Modifier element	POSTURAL COMFORT	Primary element	Modifier element
5. TOOLS AND INSTRUMENTS FOR COMFORT MEASURING	invasivity			x	aggressiveness and irritability, lack of attention		x						
	obstruction			x	work overload, level of perceived safety, aggressiveness and irritability, lack of attention		x			x	muscle effort, posture overload		x
	tactile interference	tactile sensation, localized blood pressure		x	lack of attention		x						
	restriction of movements			x	work overload, aggressiveness and irritability, level of perceived tiredness, lack of attention		x			x	muscle effort, posture overload, muscle complaint		x
	visual limitation			x	level of perceived safety, aggressiveness and irritability, level of perceived tiredness, lack of attention		x						
	override of action/ position			x	level of perceived safety, aggressiveness and irritability, level of perceived tiredness, lack of attention		x			x	muscle effort, posture overload, muscle complaint		x

Fig. 1.13: Comfort-framework for Evaluation devices

In the matrix, you can see that the most important effects in the postural comfort are muscular effort and postural overload and the factor “time of postural keeping with/without load” that belongs to the second class, causes and affects both effects. As stated in [144], people remaining in the same position for long time suffer of muscles’ stress and their posture becomes uncomfortable. The most important effects on the physiological comfort are body temperature, pulse rate and tactile sensation, for example, these effects have a different impact in function of the “lifestyle”. Aggressiveness, nervousness, degree of tiredness, stress and distractions have effects on the cognitive comfort and are mainly related to the characteristics of the working environment and degree of satisfaction. The main effect related to the environment comfort is the level of safety that depends by the organization of the layout and the keeping of the environment.

1.8 This PhD thesis

The next chapters of the PhD thesis will give answers, sometimes partial, to the research questions (see Fig. 1.14).

Chapter two shows a method to correlate the body posture of users to his postural comfort perception. The study and the experimental tests were performed in specific conditions in order to evaluate, as best as possible, only the postural effects on perceived (dis)comfort, with the purpose to understand the “Range of Rest position” (RRP) for human articular Joints. These RRPs are the position correlated with the highest comfort.

In chapter three, the concept of RRP has been used as starting point for defining the functions that links the human joint positions to the perceived postural comfort. The work is based on several experiments and was focused on the human upper limbs in static positions.

In chapter four, the Expectations effects on perceived comfort have been investigated. The comfort of the same product was tested in two conditions with a high and low expectation. The study was performed in order to check and validate the Hypothesis of the influence of the Expectation on comfort and discomfort.

In chapter five, the effects of external (emotional/cognitive) and environmental factors on global comfort perception have been investigated through a “Product Judgement” analysis of a car seat made by experts and non-experts.

In chapter six, the effect of interface temperature between human and artefacts (Mattresses) has been investigated in order to understand how the temperature is changed, and what the corresponding physiological effects are. Also, how it affects the perceived comfort is studied.

In chapter seven, the combined effects of posture, pressure and load distribution have been investigated in order to understand the combined effects on physical and physiological behaviour of the human body and, in consequence, to correlate the perceived comfort in different conditions.

Finally, in chapter eight, an example of a Comfort-driven design is given in which the findings of the PhD are applied.

In the discussion and conclusion chapter, an attempt is made to answer the four research questions, by proposing a general method for facing the (dis)comfort issue.

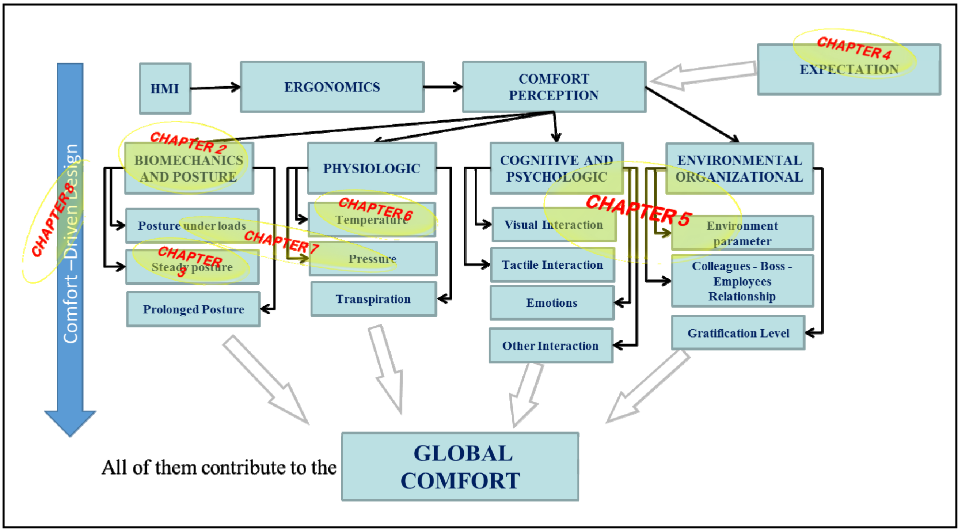

Fig. 1.14: How to navigate into the PhD Thesis

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Chapter 2

Postural Comfort Evaluation: Experimental Identification of Range of Rest Posture for human articular joints

2 Postural Comfort Evaluation: Experimental Identification of Range of Rest Posture for human articular joints

2.1 Summary

The state of the art regarding comfort/discomfort evaluation shows the need for an objective method by which to evaluate 'effects in the internal body' and 'perceived effects' according to the scheme of comfort perception by Moes [1] and Vink & Hallback [2]. Postural comfort is one aspect of comfort/discomfort perception, and this work adds to existing knowledge about posture evaluation.

The study of postural comfort begins from the study of the posture and, consequently, of the human joints' configuration and their influence on postural comfort.

In order to develop a more objectified evaluation of the postural comfort, in this work, the authors introduce and describe the Range of Rest Posture (RRP) – a new concept in human postural measurement that appears to be of use for comfort evaluation. The study is focused on the identification of RRP within the Comfort Range of Motion (CROM) for the following human joints: neck, shoulder, elbow, wrist and ankle.

The method is based on extensive experimental work involving 85 healthy individuals (43 males and 42 females) ranging from 20 to 30 years old. The age range was so narrow in order to avoid an age-clusterization of results due to unhomogeneity of the statistical sample. The experimental data were processed using statistical methods for identifying the RRP in the experimental CROM. Several Maximum Level of Comfort (MLC) positions in the RRP have been found too. These positions appear to be the most important information in comfort evaluation analysis.

2.2 Introduction and state of the art

Postural comfort can be defined as a measure of the 'level of well-being' perceived by humans when interacting with a working environment. This level is very hard to detect and measure as it is affected by individual judgments that can be analysed using quantitative/qualitative methods; however, it always varies according to the angles of the articular joints that characterise the worker's body during the execution of the task.

In the past 30 years, more than 100,000 scientific papers have dealt with comfort and discomfort. Most of these address the relationship between environmental factors (such as temperature, humidity, applied forces, etc.) that can affect perceived comfort/discomfort [2]. Several papers follow the assumption that there is a relationship between self-reported discomfort and musculoskeletal injuries, and that these injuries affect perceived comfort [4]. However, the theories relating comfort to products and product design characteristics are rather underdeveloped. The few papers explaining the concept of comfort are Helander and Zhang [5], De Looze et al. [6], Moes [1], and Kuijt-Evers et al. [7]. A literature overview allows to identify five main topics about the relationship between the subjective perception of comfort/discomfort and product/process/interaction/environment/user factors:

1) *Sensory input* (De Korte et al. [8] and Vink et al. [9]);

2) *Activities during the measurement that influence comfort* (Groenesteijn et al. [10], and Elegits et al. [11]);

3) *Different body regions* (Franz et al. [12], and Kong et al. [13]);

4) *Effect of contour of the product for the comfort experience* (Kamp [14], Naddeo et al. [15] and Noro et al. [16]);

5) *Physical loading* (Kee et al. [17], Naddeo et al. [18] and Zenk et al. [19]).

On these bases, [7] gives an interesting schematization of the comfort/discomfort perception mechanism that comes from the model by Moes' [1] in Fig. 2.1:

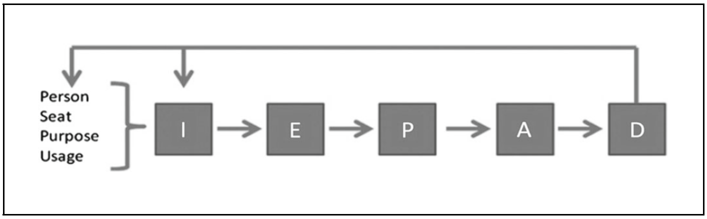

Fig. 2.1: Moes model of discomfort perception

In this model, five phases in the process preceding discomfort are represented: (I) – interaction; (E) - effect on the internal body; (P) -

perceived effects; (A) - appreciation of the effects; and (D) – discomfort. Moes (2005) also states that this process is dependent on the person, the seat, the purpose, and why the seat is used. If, for instance, a person uses a seat with a specific purpose, the interaction (I) arises. For example, this interaction can consist of the pressure distribution of the contact area between the subject and seat. An interaction results in internal body effects (E), such as tissue deformation or the compression of nerves and blood vessels. These effects can be perceived (P) and interpreted, for instance as pain. The next phase is the appreciation (A) of the perception. If these factors are not appreciated, it can lead to feelings of discomfort (D).

This model has been modified by [2] in Fig. 2.2.

The interaction (I) with an environment is caused by the contact (this could also be a non-physical contact, such as a signal in the study of De Korte et al. [8]) between the human and the product and its usage. This can result in internal human body effects (H), such as tactile sensations, body posture change, and muscle activation. The perceived effects (P) are influenced not only by the human body effects but also by expectations (E). These are interpreted as comfortable (C), no feeling (N), or leading to feelings of discomfort (D).

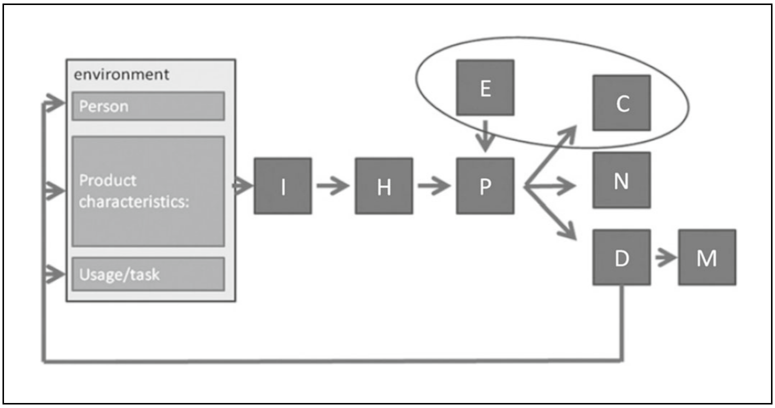

Fig 2.2: Vink-Hallbeck model of comfort/discomfort perception

In this model, the internal body effects and the perceived effects play a fundamental role in the comfort/discomfort perception/evaluation. Defining the Maximum Level of Comfort (MLC) positions for human postures appears to be one of the most important tasks in this kind of comfort evaluation model [20,21], especially when based on measurements for the angular Range of Motion (ROM) of each joint.

Some medical studies show that each joint has its own natural Rest Posture (RP) [22,23]. In this RP, the muscles are completely relaxed or at minimum strain levels, where the geometrical configuration corresponds to the natural resting position of the arms/legs/neck and so on. This position seems to minimize musculoskeletal disease and optimize comfort perception [3].

No studies seem to deal with the problem of the identification and use of the RP in ergonomic/comfort evaluation. A 1999 paper shows an application in which the "neutral zero position" is defined as a parameter for calibrating a mechanical instrument for measuring the neck's ROM. Another paper on RP deals with the postural configuration of spacemen/women [24,25]. In this study, the authors investigate how a prolonged absence of gravity can affect the body's postural configuration in a resting position. Even interesting for the RP topic, the results of the latter cannot be used for authors' purposes here.

This work seeks to develop a new method for the objective evaluation of both internal body effects (such as posture and muscle activation) and the perceived effects on several body parts based on the RRP. The work is focused on a numerical/experimental method for the individuation of RRP inside the CROM for the following human joints: neck, shoulder, elbow, wrist and ankle. Those ranges are combined to create a posture evaluation method that is useful in assessing the whole range of comfort/discomfort perception. In this study, the H-Point position was not taken into account as CROM and RRP can be defined for each human joint independently from the behaviour of the H-point. Future whole-comfort evaluation methods, however, will clearly have to take the H-Point position into account because, in DHM, the The H-point (or hip-point) is the theoretical, relative location of an occupant's hip: specifically the pivot point between the torso and upper leg portions of the body; H-point is usually used to define the lower-limbs' joints positions.

2.3 Methods

2.3.1 Comfort Range of Motion

Each ROM describes the limits of variability of a human joint. The authors have defined each ROM using references taken from several orthopaedics treatises [26].

In natural human-ROM (for each joint) there is a subset of positions in which humans remain ‘in comfort’. This subset can be defined as the CROM. There are no existing bibliographic sources to tell how to determine the width of ROMs or how to describe and identify the CROM within the ROM. This work presents a new experimental method for checking the natural human ROMs and determining the CROMs for each human joint that should be taken into account when performing comfort evaluation.

The hypothesis is as follows: *For each human joint, it is possible to define one function that represents the articular range of motion. This is also true if the joint displays different articular limits for different percentiles, gender or other characteristics.*

This hypothesis is valid when the studied postures are far from the articular limits that define the critical postures for ergonomic standards. In the studied case, this is true as comfort studies take into account only those postures that give a very good ergonomic evaluation.

The study checks and defines the CROM for the following human joints and their Degrees of Freedom (DOF) [29-35]:

- Neck: flexion/extension, lateral flexion (bending), rotation [27-28];
- Shoulder: flexion/extension, abduction/adduction;
- Elbow: flexion/extension, pronation/supination;
- Wrist: flexion/extension, radio-ulnar deviation;
- Ankle: dorsal-plantar flexion.

For each joint’s DOF, the CROM are defined as the intersection (Fig. 2.3) of the suggested comfort range across several bibliographical references [35,36].

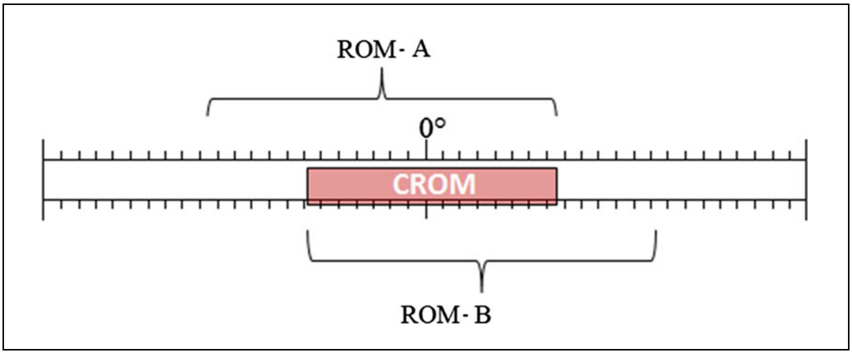

Fig. 2.3: Intersection between two ROMs

2.3.2 Range of Rest Posture (RRP)

Each human, due to the uniqueness of his/her body anatomy, feels ‘in comfort’ in several positions. However, only one position is recognized as the RP. This is true for every joint considered, and has been verified that the RP is different for each individual. When analysing data from experimental tests, the identified RPs must be processed using a statistic approach to extract synthesized (and valid) data for the whole statistical sample. For this reason, this work introduces a new subset of positions in which articular joints can be considered ‘statistically’ at rest. This range, that is a subrange of CROM, has been named as the ‘Range of Rest Posture’ (RRP – Fig. 2.4), with each angular value in the RRP being that which produces the maximum joint comfort.

Fig. 2.4: Definition of RRP

Statistical analysis of acquired data is used to identify the width and position of the RRP in the ROM. This analysis starts with experimental planning to define the research target and information extrapolation method. The statistical sample size and the evaluation of comfortable postures allows to identify the RRP.

The RRP is determined from two kinds of postural configuration:

A. Standing human
B. Seated (like in fig. 2.11) human

These configurations are the most probable, widespread and significant in any working environment. They allow to detect several relevant data, and as such were selected for the laboratory tests.

2.3.3 Experimental Rest Posture Measurement

The experimental tests start with the collection of those anthropometric measures [29,37] needed to select the percentile of the human sample and to define the RP for each joint. This phase uses a photographic survey method and image processing software. The former allows to collect information about joints without the use of invasive/contact systems that can often limit or affect the natural positioning of the joints. The latter is a fast, safe method of extracting and managing the information.

The photographic environment was composed of a closed black-walled laboratory, a photo-camera on a tripod, a Cartesian reference system, and the individual to be photographed; it is designed to enable posture acquisition in both standing and seated positions. The black wall behind the subject is equipped with a scaled grid that acts as a reference for taking angle measurements. The reference system is calibrated to avoid and/or predict errors[6] due to the barrel/pillow effect.

The human body, ideally made by segments of representative 3D dimensions, is modelled using a schematized multi-body system in which the joints are connected by segment lines (a segment, for example, stands for an arm). Angles are defined between/around these lines.

Information about the photographic environment is shown in the following Fig. 2.5.

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[6] Errors are always below the 4%

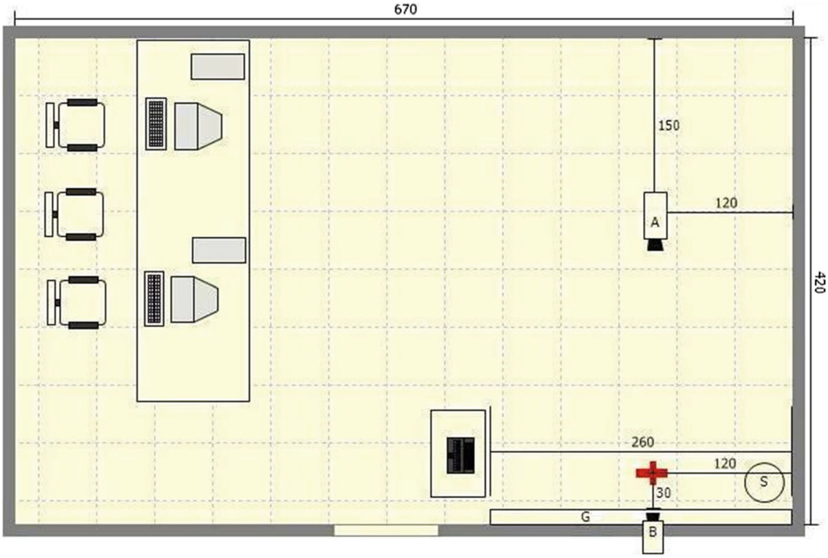


Fig. 2.5: Laboratory layout

A: Digital camera Samsung D60: focus height = 1.20 m on a rigid tripod that is fixed to the ground;

B: Digital Webcam Logitech: focus height = 2.20 m on a rigid tripod that is fixed to the ground;

G: Uniform grid (2.60 m x 2.00 m), printed on a paper sheet (more than 200 g/m2) affixed rigidly to the wall;

S: A chair with a full-tuning seat (in height) for taking pictures of ankles (hanging legs), with a system for taking angular measurements.

*: Body position for pictures in the frontal and sagittal planes (Camera A) and in the transverse plane (Camera B).

Kinovea® release 0.8.7 software was used for image processing.

The chosen statistical sample consists of 43 male and 42 female university students. Heights ranged between 149-195 cm; ages ranged between 20-40 years old; and there was an absence of muscular-skeletal diseases.

Pictures taken during the photographic session were modified in order to correct the ‘fisheye and distortion’ effects due to camera positioning. The corrective factor was calibrated by comparing the picture of the uniform grid with the uniform grid (in Fig. 2.6).

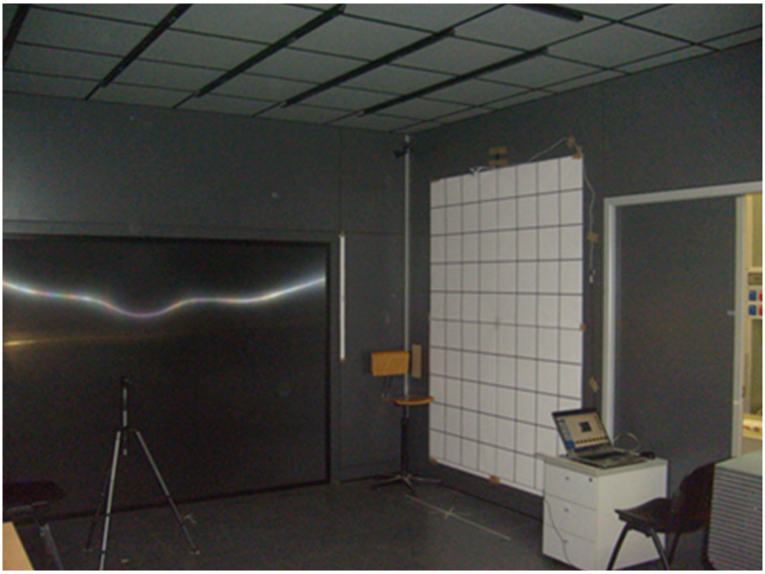


Fig. 2.6: Closed black-walled laboratory

Subjects were trained in the experimental procedure and work targets. The following paragraph describes the DOF involved in the measuring procedure and the photographic analysis. The shoulder articular joint, whose DOF are linked to arm movement, can be easily checked and measured in the BP by positioning a relaxed arm (both left and right) along the body (thorax) near to the geometric-zero position (Fig. 2.7). The picture can then be taken with the subject in this position. The same procedure works well for both RPs of the arm. The only change required is to the photographic plane.

To measure the angle, the following reference points are required:

1. Humerus head: identified as the centre of the circle defined by three points taken (positioned) on the shoulder;
2. Elbow centre: the ideal centre of the sphere identified by four points (not aligned and not belonging to the same plane) taken on the elbow;
3. Wrist centre: the ideal centre of the sphere identified by four points (not aligned and not belonging to the same plane) taken on the wrist;
4. Ankle centre: identified as the centre of the circle defined by three points taken (positioned) on the ankle;
5. Head centre: the ideal centre of the sphere approximating the skull bones.

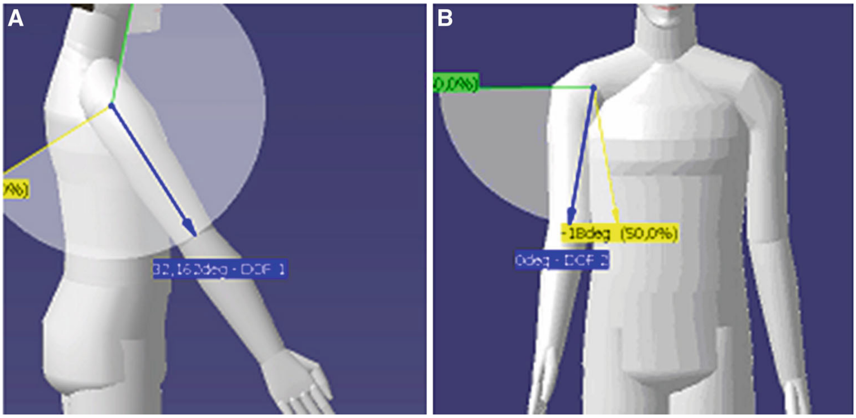


Fig. 2.7: Shoulder DOF

The shoulder measurements have been taken after the photographic session:

- Flexion/Extension (A) is defined as the angle between two segments. The first of these is along the arm axis; the second, in a vertical direction, starts from the humerus head.
- Abduction/Adduction (B) is defined as the angle between two segments. The first of these is along the arm axis; the second, in a vertical direction, starts from humerus head.

The measurement of the forearm in a neutral position, which is used for defining elbow articulation, was taken starting from the zero-geometric position, with the subject requested to fully relax.

Two kinds of measurement refer to the elbow joint (fi. 2.8):

- Flexion/Extension (C) is defined as the angle between two segments. The first of these is oriented along the line passing through the humerus head and the centre of the elbow; the second is oriented along the arm's axis and passes through the centre of the elbow;
- Pronation-supination (D-E-F): the definition of this ROM is more difficult as it requires a blocking a bracelet on the subject's wrist with a rigid pin fixed in parallel to the 'thumbs-up' position. This measurement was calibrated as follows: the pin must be orthogonal to the frontal plane when the arm is in the geometric-zero position. Next, the subject is asked to completely relax their arm, causing the wrist to naturally rotate around its axis (arm axis). However, it is impossible to capture a picture for measuring the rotation in this position. To overcome this problem, a 90°

rotation of the arm around the elbow articular joint was imposed using a passive guided motion (PROM). This configuration allows the measurement to be taken with a single picture.

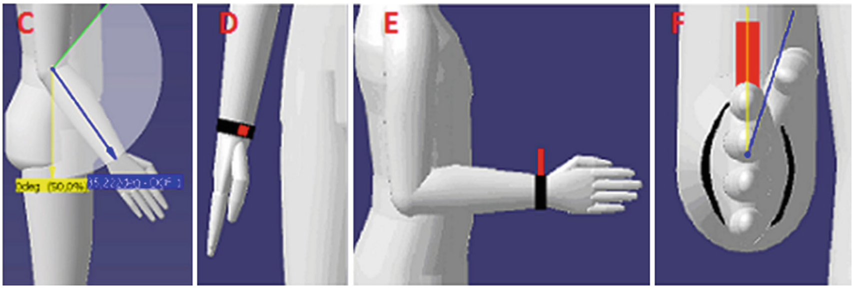


Fig. 2.8: Elbow DOF

The RP of the hand was characterized using wrist RRP, flexion-extension, and radio-ulnar deviation (Fig. 2.9), as follows:

- Flexion-extension (G) is defined as the angle between two segments. The first of these is oriented along the prolongation of the arm axis; the second is oriented along a line passing through the base of the thumb and the first phalanx of the index finger in a straight position.
- Radio-ulnar deviation (H) is defined as the angle between the prolongation of the arm axis and a second segment along a line that passes through the centre of the wrist and the conjunction point between the middle finger and the ring finger on the metacarpal bone.

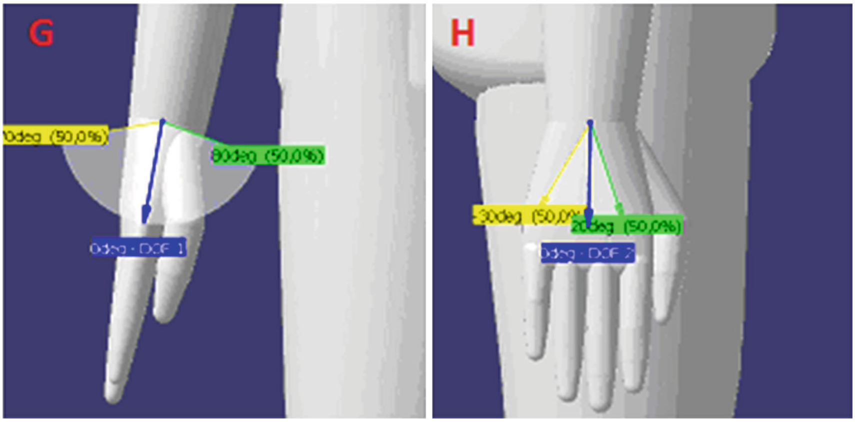


Fig. 2.9: Wrist DOF

Experimental analysis revealed a particular behaviour of the hands. Gravity significantly affects hand position by conditioning the position of the wrist's articular joint. The zero-geometric position is hence coincident with RP in this instance.

The neck articular joint, and its three RPs, can be measured in the same way as the other joints by asking the subject to close their eyes and relax. This set-up limits the influence of external references and environmental factors for the test subject.

RPs are defined as follows (Fig. 2.10):

- Flexion/Extension (I) is defined as the angle between the horizontal plane (parallel to ground) passing through the centre of the ears (under the 'head symmetry' hypothesis) and a plane defined by three points: the same two ear centres and the nose base. These are the only parameters defined using a method different from that suggested by posturologists. This choice was made due to the ease in defining the angle using pictures taken by a single camera.
- Lateral flexion (L) is defined as the angle between two segments. The first of these is a vertical line passing through the centre point between the scapulae; the second is a line passing through the same centre and the central point between the eyes.
- Rotation (M) is defined as the angle between the segments defined using humerus' heads and a segment passing through the rotation centre of the neck and the nose base, projected on the ground plane.

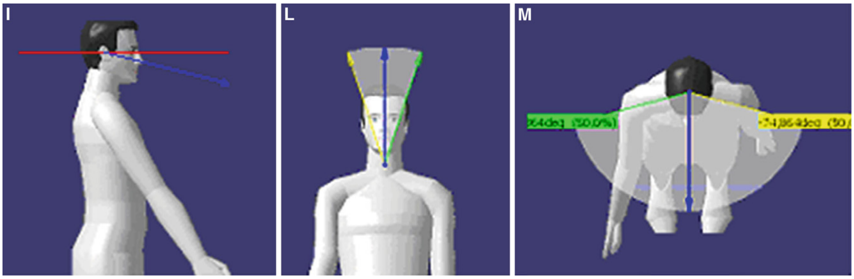


Fig. 2.10: Neck DOF

For ankle joint measurement in the RP (Fig. 2.11), the subject was seated on a chair with their feet hanging in the air.

- Dorsal-Plantar Flexion (N-O) is defined as the angle between two segments. The first of these is a line passing through the centre of the knee (under the 'posterior ligament') and the malleolus; the second is a line passing through the same centre of the malleolus and the median point between the second and third metatarsus.

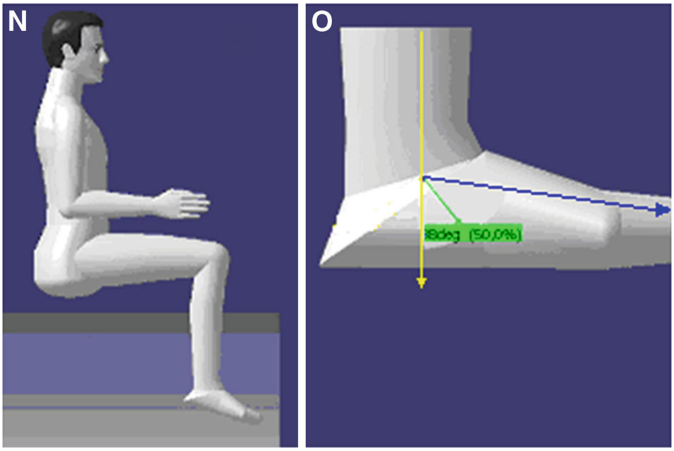


Fig. 2.11: Ankle DOF

Figure 2.12 shows several pictures used in angle measurements.

Fig. 2.12: Male angle measurements

2.4 Results

Data acquired in the experimental phase were organized on the basis of the subject's characteristics (gender, age, weight, height, percentile, BMI) and by the DOF of the articular joints. These were then processed using statistical techniques.

Using inferential instruments, a continual distribution function was individuated for each articular joint DOF [30]. The procedure applied for the pronation-supination of female elbow analysis is described in the following paragraph. All articular joint data was processed in the same way.

Range	Frequency
−51.0 to −42.2	2
−42.1 to −33.3	1
−33.3 to −24.5	5
−24.5 to −15.7	19
−15.7 to −6.8	10
−6.8 to 2	5

Tab 2.1: Prono-supination of the female elbow

Collected data was analysed to choose the probability distribution that best represents them (from Normal, Weibull and Lognormal). For this kind of data, the optimal distribution is clearly the "3-parameter Weibull". Table 2.1 and the following Figures 2.12, 2.13 and 2.14, show an example of this:

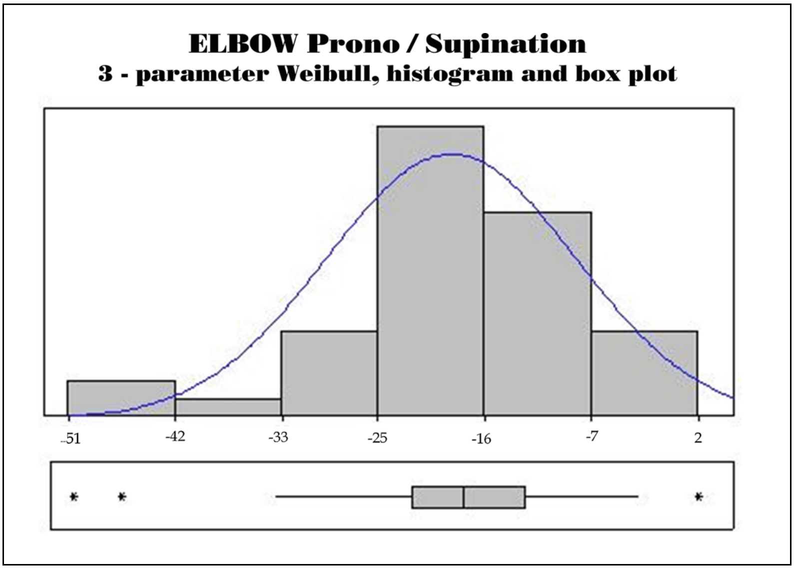


Fig. 2.13: Box plot

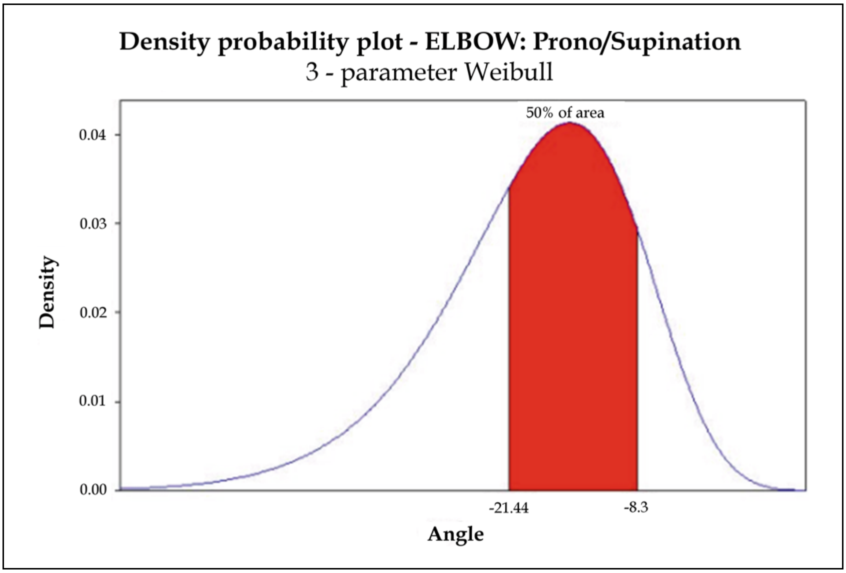


Fig. 2.14: Density probability plot

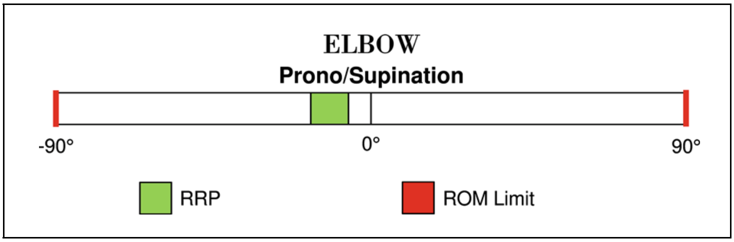


Fig. 2.15: Summary of results

Using the chosen statistical distribution, it is possible to define the range of a value. The ROM was defined in the main range, in which was considered that the articular joint is in the RP. This range, defined as Range of Rest Posture (RRP), was chosen as the domain for which the area (centred on the mode value - see the previous images) under the Weibull curve is about 50% of the total Weibull area.

The same analysis for the female elbow articular joint was made for all the studied articular joints. The optimal statistical distribution to define the RRP was used for each. Results are graphically shown in the following Figures (2.16 to 2.23).

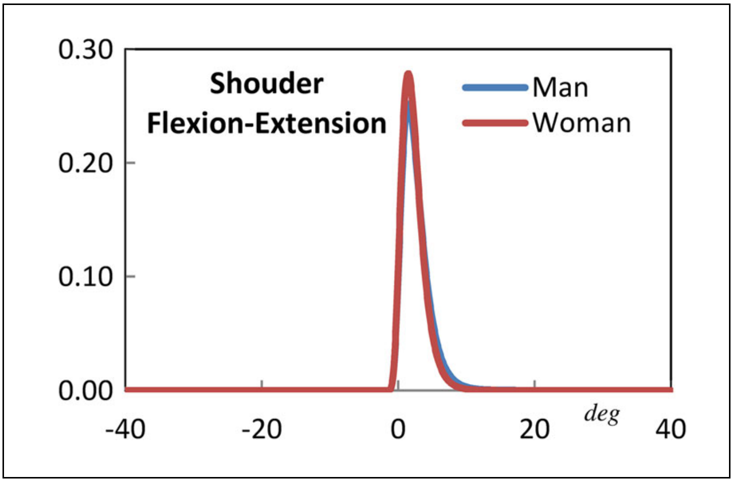


Fig. 2.16: Distribution of shoulder flexion-extension Rest Posture

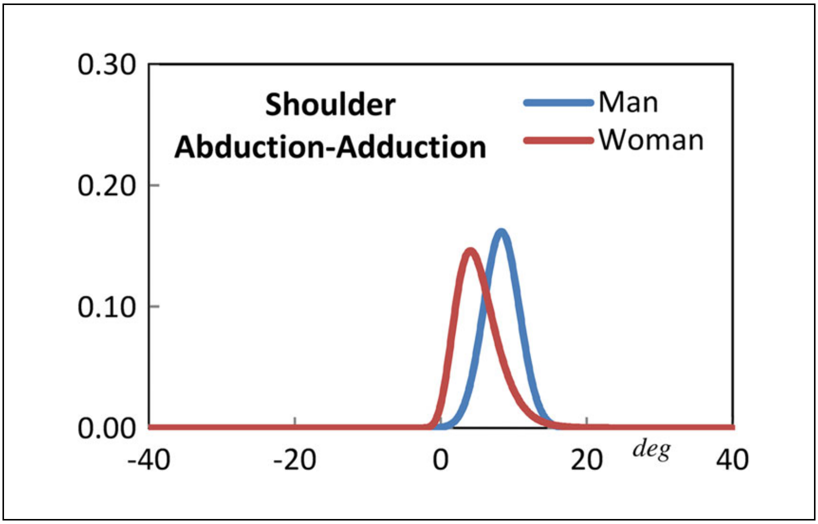


Fig. 2.17: Distribution of shoulder abduction-adduction Rest Posture

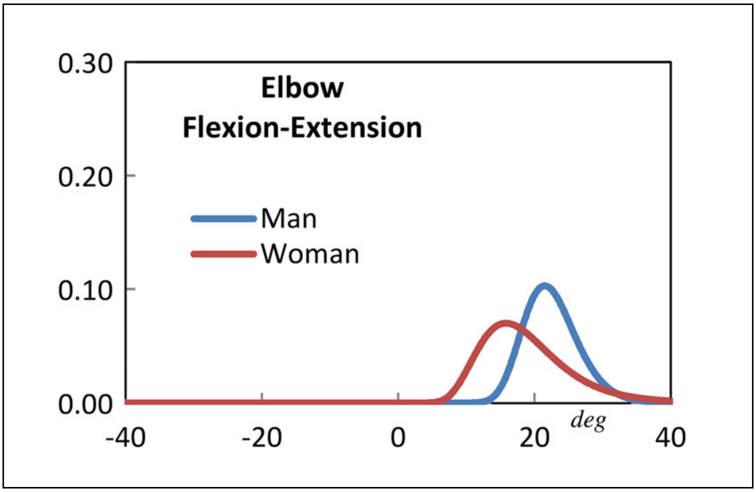


Fig. 2.18: Distribution of elbow flexion-extension Rest Posture

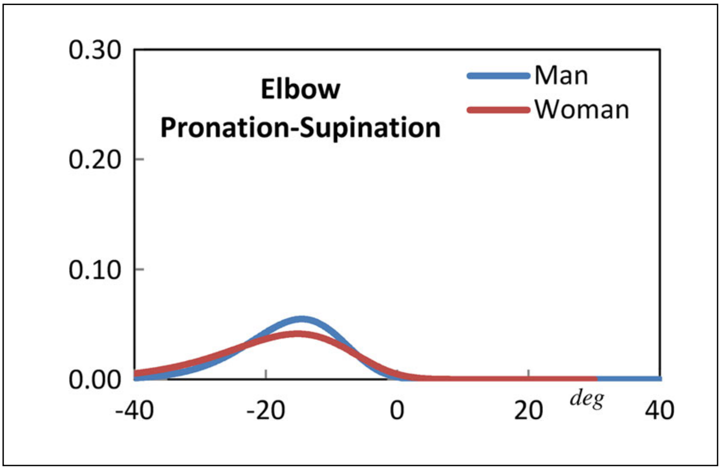


Fig. 2.19: Distribution of elbow prono-supination Rest Posture

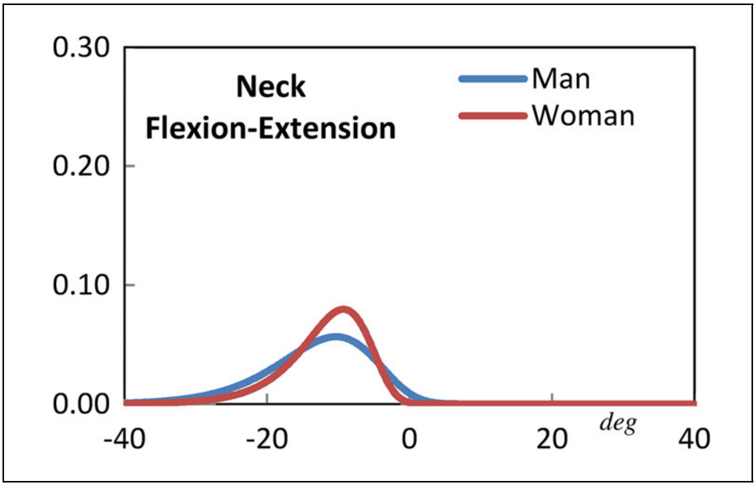


Fig. 2.20: Distribution of neck flexion-extension Rest Posture

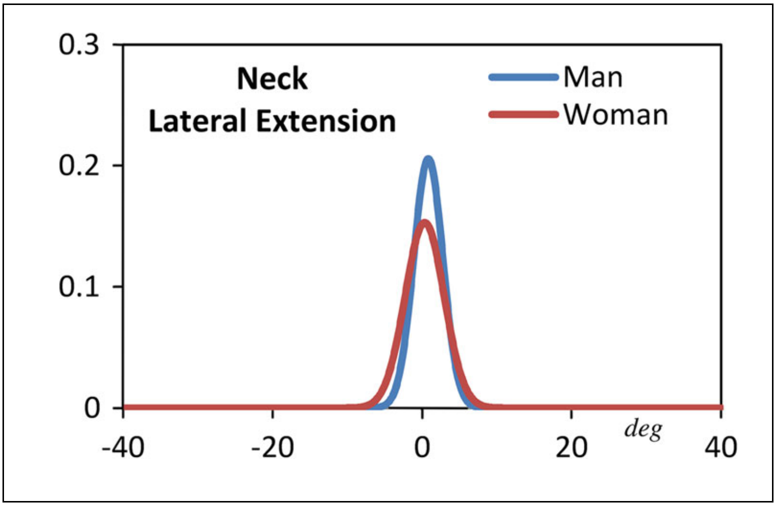


Fig. 2.21: Distribution of neck lateral extension Rest Posture

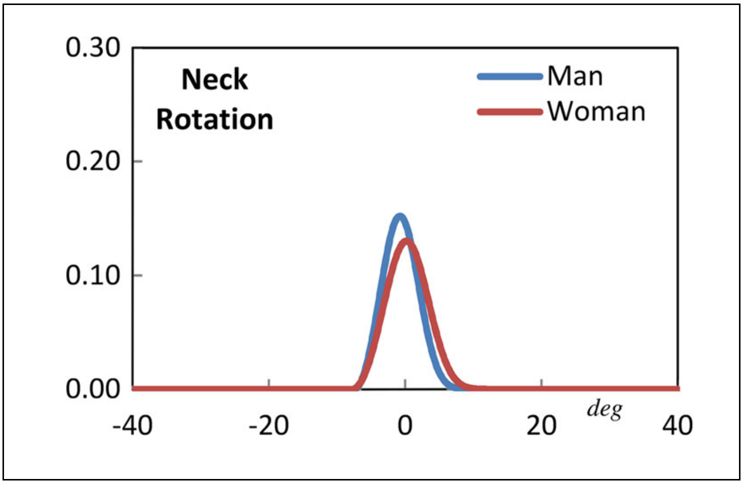


Fig. 2.22: Distribution of neck rotation Rest Posture

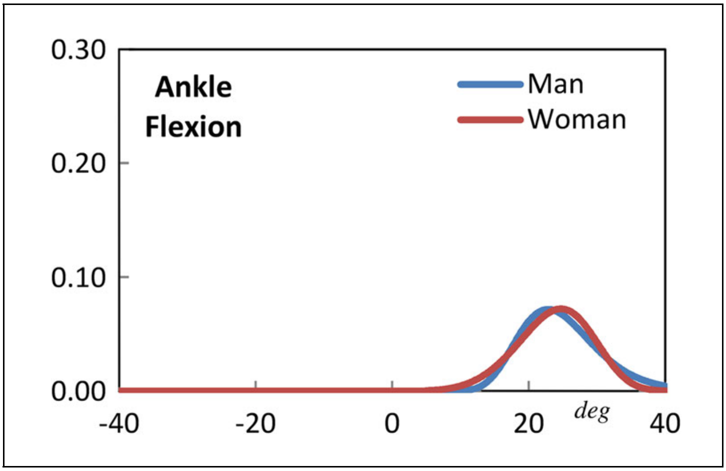


Fig. 2.23: Distribution of ankle flexion Rest Posture

2.5 Discussion

Certain parameters such as shoulder abduction/adduction RP distributions are well modelled by asymmetric curves, as RP is strongly affected by gravity (due to the arm's own weight) and by the nearness of the arm to the body.

The same behaviour is seen in articular joints whose RP is affected by the body-part weight. The counter-proof is given by the neck behaviour, whose RP distribution has the shape of a Gaussian curve, with the mean centred in a value coincident with mode and median values.

All statistical distributions representing the behaviour of the articular joints follow those suggested by posturologists.

Interestingly, this experimental analysis reveals that no differences can be highlighted between male and female behaviours. This realisation may allow to define just one RRP for each joint's DOF for the whole statistical sample, as well as providing limits to the ROM for the entire population. ROM is defined as the intersection of all ranges of motion displayed by the subject. The following Figures (2.24 to 2.28) present a review of ROM and RRP.

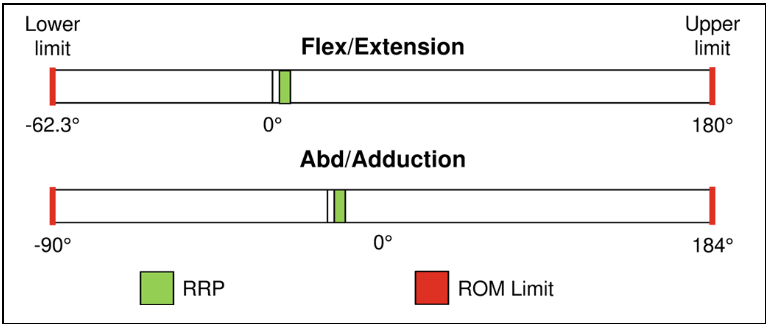


Fig. 2.24: Shoulder RRP and CROM

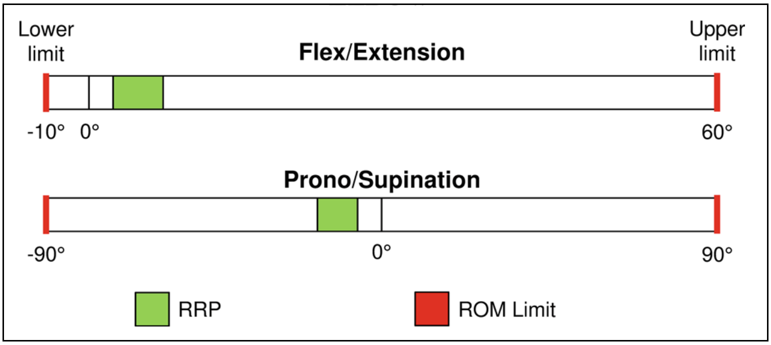


Fig. 2.25: Elbow RRP and CROM

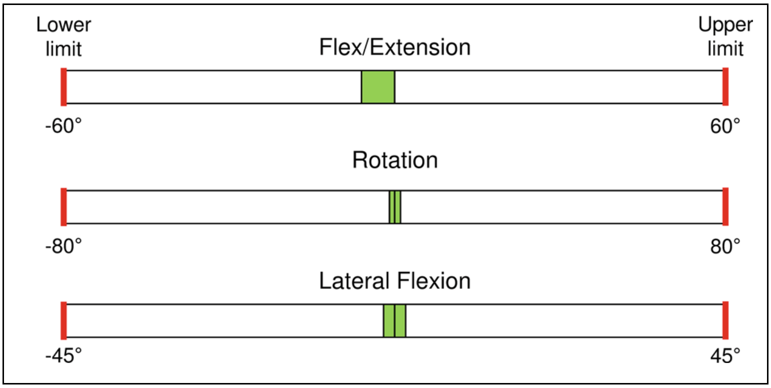
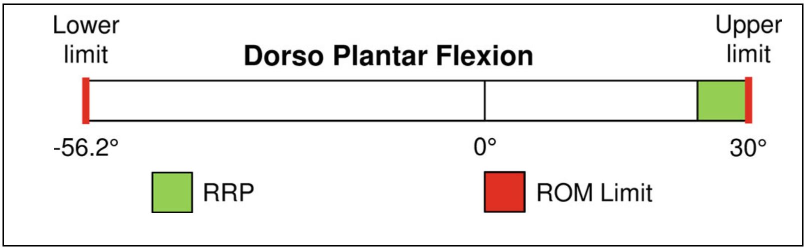


Fig. 2.26: Neck RRP and CROM



Fig, 2.27: Ankle RRP and CROM

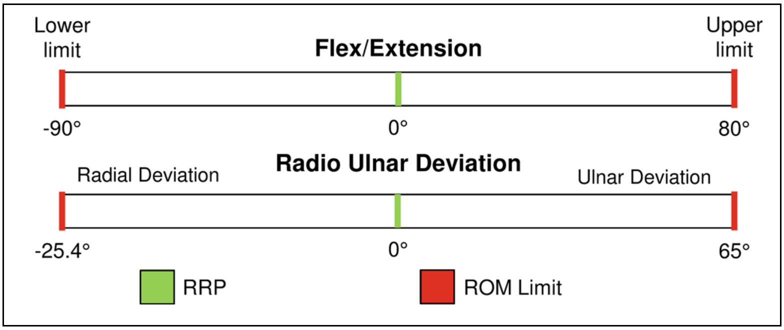


Fig. 2.28: Wrist RRP and CROM

At this stage in this research, only postures that involve the seated position and the standing position were investigated, without loads applied. In these positions, the H-Point does not affect the behaviour of the joints, and is therefore not taken into account.

At this stage, no rules for combining joint comfort values have been implemented. Even if the development of an evaluation rule seems necessary for industrial application, the authors would like to conduct further investigation into the way that joints may be evaluated for different industrial applications.

There are some parameters that are not affected by positioning the body in either the standing or the seated position (e.g. neck parameters). Other parameters, however, are strongly affected by the RPs of the shoulders or legs.

Another investigation to be carried out is the rest-posture evaluation in conditions for which one or more body-parts are resting on supports (e.g. an elbow on a table, or a wrist on a mouse) because the forces configuration, due to supports, might change the muscular activities and the ligaments/tendons work, consequently affecting the comfort perception. These configurations can be studied as free limb configurations modified with penalty/prizing functions to adjust the comfort level.

The last investigation to be carried out focuses on the changes in comfort level between free limb configurations and 'under-load' limb configurations. These postures are affected by equilibrium difficulties (due to changes in the limbs' centre of gravity) and by force factors (related to muscular-skeletal fatigue).

2.6 Conclusion

The main result of this study is the conception of a new approach to determine the postural ranges at which comfort improves for several articular joints. Another very relevant result is the determination of the exact angular ranges corresponding to RPs (as statistically defined above). These results find their utility in the modified Moes' model [1] for analysing both internal body effects and the perceived effects. This appears to be the first attempt to objectivise joint comfort performance without using EMG [37-38] or other experimental methods such as in [18], [39], [40] and [41].

Several papers such as [18], [40] and [42] deal with the question of ranges of motion. However, this work is the first in which the new concept of RRP is introduced and used to evaluate human joint comfort.

The comfort curves were obtained using data from a wide range of studies by posturologists to define the CROM of articular joints. Medical data was also used to conduct a complicated experimental phase. Experimental tests were made on two different statistical samples, with a broad enough sample size that the acquired data could not be affected by unforeseeable and illogical errors. The acquired data was then processed using statistical inference instruments to obtain a continuous curve describing the probability distribution of the RP in a representative statistical sample of individuals between 20 and 40 years old. Using these curves, the characteristic data such as the mode and the area distribution under the curve were extracted. Then, a sample for which 50% of data are distributed around the mode value was selected. This approach allowed to eliminate 'out of statistic' data (i.e. potentially not significant data). RRP, as defined in the work, can be very useful to define and evaluate maximum comfort postures for several work tasks involving the upper and lower limbs. These tasks will also be useful to identify postures whose comfort level is too low. This comfort check could be used, for example, to re-design work tasks or work spaces to improve comfort values. This appears to be the optimal application for the described and implemented method.

2.7 Acknowledgement

Experimental tests were performed in a Virtual Reality LAB (VRLab) of the Dept. of Industrial Engineering of the University of Salerno, Italy. The VRLab was set up to create the optimal environment in which to perform photographic acquisition. Many thanks to Carmine, Alessandro and Marco, whose work was untiring. Many thanks also to all the mechanical engineering and management engineering students who gave their time and patience over many hours of testing.

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Chapter 3

Proposal of a new quantitative method for postural comfort evaluation

3 Proposal of a new quantitative method for postural comfort evaluation

3.1 Summary

In Human-Machine Interface (HMI) design, several parameters have to be correctly evaluated in order to guarantee a good level of safety and well-being of users (humans) and to avoid health problems like muscular-skeletal disease. ISO Standards give a good reference on Ergonomics and Comfort: ISO 11228 regulation; it deals with qualitative/quantitative parameters for evaluating Postural Ergonomics, using a “Postural Load Index”, in push/pull, in manual loads’ lifting and carrying and in repetitive actions; those parameters can represent the Ergonomics level of examined posture. While bibliographic references suggest different methods to make ergonomic evaluation like RULA, LUBA and REBA, the state of the art about comfort/discomfort evaluation shows the need of an objective method to evaluate “effect in the internal body” and “perceived effects” in several schemes of comfort perception like Moes’, Vink& Hallback’s and Naddeo&Cappetti’s ones; postural comfort is one of the aspect of comfort/discomfort perception and this chapter proposes a new quantitative method for evaluating this aspect of comfort, based on anthropometric parameters and upper limbs posture. The target of this chapter is to present and test a “general purpose” method of comfort-measurement that can be applied to different industrial cases: in workspace environments, in automotive passenger compartments, in aeronautic cockpit or in industrial assembly lines.

3.2 Introduction and state of the art

In Human-Machine Interface (HMI) design, several parameters have to be correctly evaluated in order to guarantee a good level of safety and well-being of users (humans) and to avoid health problems like muscular-skeletal disease.

ISO 11228 is the only ISO Standard that can give a good reference on ergonomics and comfort evaluation and its parameters can be synthesized in a “Postural Load Index” that represents the Ergonomics level of examined posture [1,2] but does not give information about the perceived well-being.

Bibliographic references suggest methods like Rapid Upper Limb Assessment [3], Rapid Entire Body Assessment [4] and Loading of the Upper Body Assessment [5] to perform ergonomic analyses that go by measurement of anthropometric parameters. Postural comfort can be defined as the measure of the "level of well-being" perceived by humans when interacting with a working environment; this level is very hard to detect and measure because it is affected by individual judgments that can be analysed using quantitative/qualitative methods.

As reported in Chapter two, Vink and Hallbeck [6] gave an interesting schematization of the mechanism of comfort/discomfort perception that comes from the Moes' [7] and has been upgraded by Cappetti and Naddeo [8].

All presented models take into account the body effects and the perceived effects that are useful to define the Maximum Level of Comfort (MLC) positions in human postures and are needed to make a comfort evaluation based on measurement of the angular Range of Motion (ROM) of each joint [1, 9-11]; certain medical studies show that each joint has its own natural Rest Posture (RP) [12,13], wherein the muscles are completely relaxed or at minimum strain level: when this occurs, the geometrical configuration corresponds to the natural position of the resting arms, legs, neck, and so forth. In [14] it is demonstrated that the rest position minimizes musculoskeletal disease and optimize the comfort perception; in [11], the problem of identifying and using the RP concept in ergonomic/comfort evaluations is addressed; in [13] is presented an application in which the "neutral zero position" is defined as a parameter for calibrating mechanical instruments in measuring the neck's ROM. The RP concept has been used in Apostolico et al. [11] for experimentally identifying the Range of Rest Posture (RRP). It was demonstrated that anthropometric parameters can be used to evaluate users' well-being level (comfort), so, in present work, authors show the procedure used to build curves that represent comfort values along the entire range of postures (joint angle) for each human joint under consideration and proposes a method for postural comfort evaluation for improving the ISO standards' method.

3.3 Theory

This chapter focuses on the numerical and experimental procedure for developing a comfort evaluation method for the upper part of the human body. The authors aim to demonstrate that this approach (based on the spatial configuration of body parts) allows to define a quantitative method for comfort measurement, which is all-purpose and can be applied to different industrial cases: workplace environments, automotive passenger compartments, aeronautical cockpits, and industrial assembly lines. It can also be used in both the design phases and the optimisation and redesign phases of products and processes in order to improve the postural comfort of users/workers.

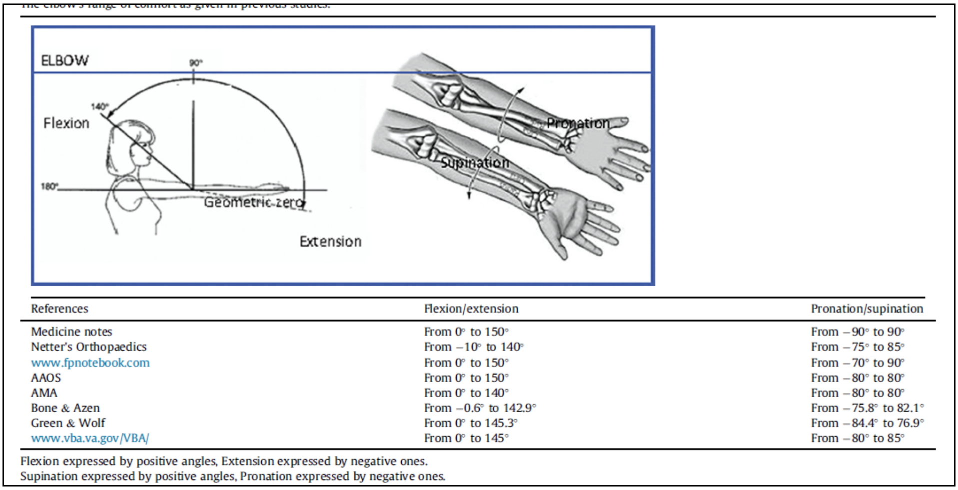
In this study, the H-point position was not taken into account because the comfort range of motion (CROM) and RRP can be defined for each human joint independently from H-point behaviour and position. For the evaluation of whole-body comfort, the H-point must obviously be taken into account.

A preliminary bibliographical analysis allows to define the domain of "comfort function" as the set of angle values that characterises the movements of human joints (ROM). This strongly depends on the subset of values corresponding to a good ergonomic level (not necessarily a comfortable one).

The following joints were taken into account along with their main movements (degree of freedom [DOF]):

- Neck: flexion/extension, lateral flexion, rotation;
- Shoulder: flexion/extension, abduction/adduction;
- Elbow: flexion/extension, pronation/supination;
- Wrist: flexion/extension, radio/ulnar deviation;

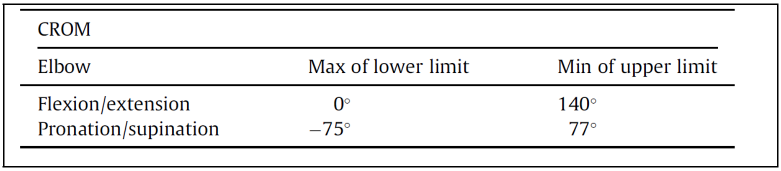
In previous studies [15-23], several ROMs were defined or suggested for each joint. It was preferred to use, as with the CROM, the intersection of all ROMs as suggested in the literature, because non-common values are probably associated with an uncomfortable posture. For example, Table 3.1 presents the elbow CROM as given in several previous studies, while Table 3.2 provides the choice for the CROM.



References	Flexion/extension	Pronation/supination
Medicine notes	From 0° to 150°	From −90° to 90°
Netter's Orthopaedics	From −10° to 140°	From −75° to 85°
www.fpnotebook.com	From 0° to 150°	From −70° to 90°
AAOS	From 0° to 150°	From −80° to 80°
AMA	From 0° to 140°	From −80° to 80°
Bone & Azen	From −0.6° to 142.9°	From −75.8° to 82.1°
Green & Wolf	From 0° to 145.3°	From −84.4° to 76.9°
www.vba.va.gov/VBA/	From 0° to 145°	From −80° to 85°

Flexion expressed by positive angles, Extension expressed by negative ones.
Supination expressed by positive angles, Pronation expressed by negative ones.

Table 3.1: The Elbow's Range of Comfort as Given in Previous Studies



CROM

Elbow	Max of lower limit	Min of upper limit
Flexion/extension	0°	140°
Pronation/supination	−75°	77°

Table 3.2: Elbow CROM (Comfort Range of Motion)

For each human joint, it is possible to define another range, namely the RRP, which is always a sub-range of the CROM and represents a subset of positions in which articular joints can be considered to be "statistically" in rest. This range is obtained from the analysis of humans whose joints are in a natural position with relaxed musculature. Each angular value within the RRP can be considered to be the maximum comfort for the joint angles [11].

The comfort evaluation method explained in this work, like previous methods, defines a mathematical model for evaluating the comfort level (by an index) when measuring joint angles in a given posture. One hypothesis taken into account is that the extremities of the CROMs represent the minimum comfort values [24,25], while the RRP [11] denotes the range of the maximum comfort values; between these values, the level of comfort is generally unknown. To investigate this, the analysis began with experimental sessions to obtain data on the judgment of several types of postures and then elaborated these data using statistical methods. Finally, the data were synthesised, leading to the definition of the comfort versus posture curve using a neural network.

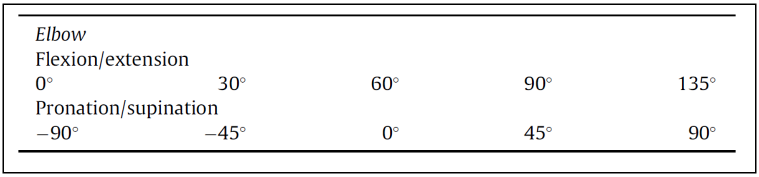
3.4 Methods

The standard Galilean method has been used. The experimental evidence has been used to extrapolate a general comfort evaluation law, before testing it, in order to achieve a good numerical and experimental level of reliability.

The chosen experimental sample comprises 100 persons with the following characteristics:

- Aged between 20–30 years;
- 50% men and 50% women;
- Not affected by muscular-skeletal diseases.

Subjects were previously informed about the procedure and objectives of the tests.



Elbow				
Flexion/extension				
0°	30°	60°	90°	135°
Pronation/supination				
−90°	−45°	0°	45°	90°

Table 3.3: Example of domain division for Elbow's CROM

The CROM for each joint was divided into four sub-ranges, as in the LUBA method [5], by identifying the five main angular values, like in the example in Tab.3.3.

We asked subjects to perform several simple actions for each joint in a 6-DOF (A system with only 6 Degree of Freedom – 3 for translation and 3 for rotation) system. The actions were studied and simulated to better uncouple the DOFs from each other; each action took about 10 seconds for the subject to complete. This value was chosen so that the time spent to express a good comfort judgment, can be considered as a parameter that does not affect the same judgment. The "fatigue factor" (also known as muscular-stress or strength factor) was ignored.

Experimental tests provided subjects with the possibility of expressing a comfort rating for each joint and for some chosen postures; the postures were always chosen within CROM bounds, with the evaluation scale ranging from 1 (minimum score) to 10 (maximum score).

Authors asked to subjects to make the joints' movement without moving other body-parts, when possible, in order to better uncouple the joints each other.

Evidently, all acquired data are affected by ungovernable variance due to the subjectivity of participants' perception and the lack of uniformity in the data. Hence, it is difficult to use mathematical functions (approximation or interpolation) to build a valid model for describing the relation between joint angles and comfort. Therefore, it is required a mathematical instrument that was not heavily affected by participants' subjectivity to allow to be free from the subjective results of the sample and create a general law for function comfort versus angles. This kind of mathematical model must be developed using data from experimental tests and provide a comfort value for each possible human posture. For the subjectivity-independent experimental work, a neural network (NN) was used [26,27] to create this variability model. The aim of the NN is to establish the correlation function between angular values and experimental comfort scores. The NN was developed using the following data:

- RRP taken from Apostolico et al. (2013), in which comfort is considered to be the maximum (see the Chapter 2);
- Boundary values of CROM, in which comfort is considered to be the minimum;
- Data from the subjects using the procedures above described.

It is useful to highlight that for some articular joints, such as elbows, the natural rest position (180° in flexion-extension) is very close to the natural ROM bounds, meaning that the maximum comfort value approaches the bound of CROM (see Table 3.1).

3.4.1 Performed tests

Tests were conducted in the VR-Lab at the University of Salerno. The main room was designed to obtain the setup shown in Fig. 3.1. Angles were measured using photogrammetric analysis. All tests were performed by a standing or seated subject and without applied loads. Each subject has been modelled, in advance, by the DHM (Digital Human Modelling) DELMIA software, by Dassault Systemes, in order to better position him/her while performing the tests.

A paper sheet was placed on the wall to calibrate cameras and correct all photographic errors (fisheye effect, perspective errors, etc.).

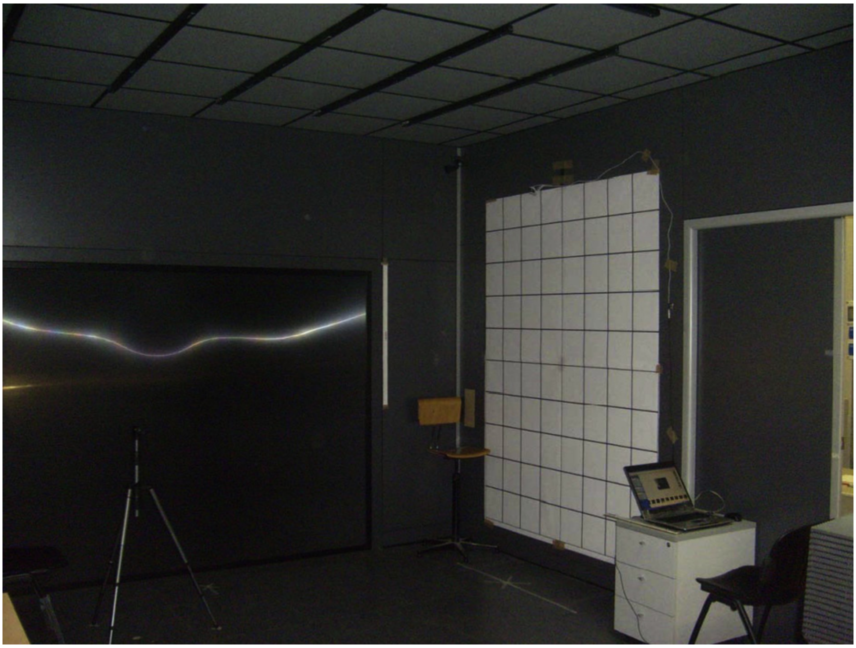
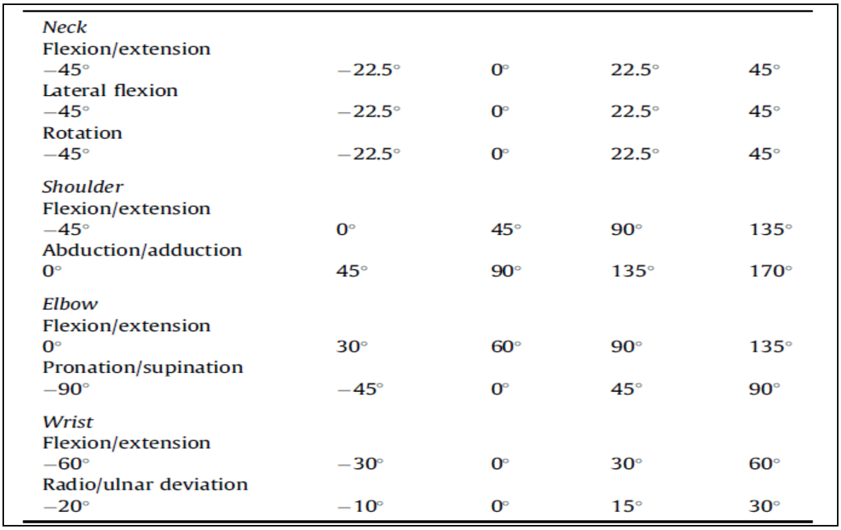


Fig. 3.1: VR-Lab set-up: graduated paper sheet and acquisition devices



Neck				
Flexion/extension				
−45°	−22.5°	0°	22.5°	45°
Lateral flexion				
−45°	−22.5°	0°	22.5°	45°
Rotation				
−45°	−22.5°	0°	22.5°	45°
Shoulder				
Flexion/extension				
−45°	0°	45°	90°	135°
Abduction/adduction				
0°	45°	90°	135°	170°
Elbow				
Flexion/extension				
0°	30°	60°	90°	135°
Pronation/supination				
−90°	−45°	0°	45°	90°
Wrist				
Flexion/extension				
−60°	−30°	0°	30°	60°
Radio/ulnar deviation				
−20°	−10°	0°	15°	30°

Table 3.4: Sub-ranges of Motion for comfort evaluation

Each Joint's CROM has been opportunely divided in sub-ranges (Table 3.4); to subject were asked to move his/her joints in different position (previously modelled, by DELMIA™, inside each sub-range) and to express a comfort rate between 0 and 10 for each of them.

3.4.2 Neck joint test

To test the neck joints, a small white board with a written text was prepared. Subjects had to read the text at a distance of 80cm, while focusing their eyes on a specific point on the paper (Fig. 3.2).

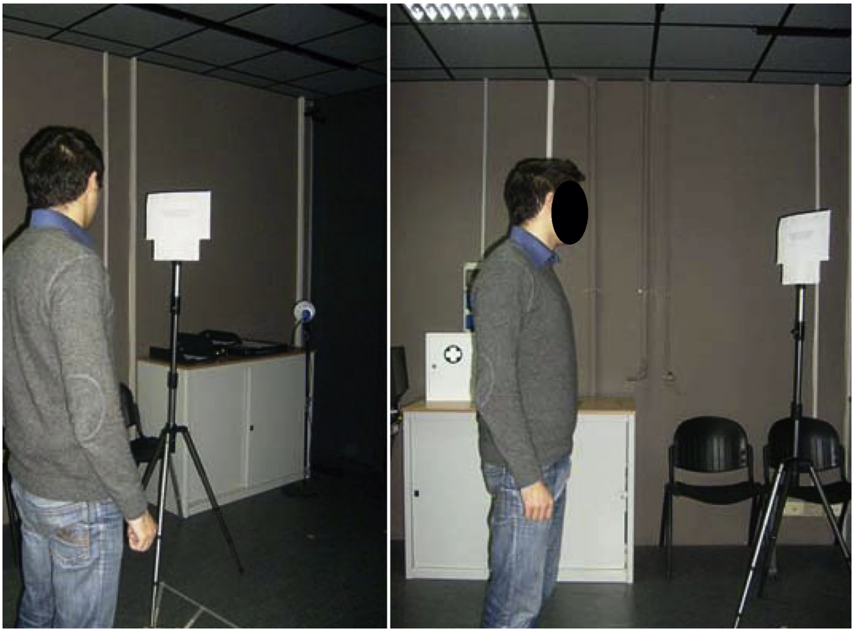


Fig. 3.2: Neck joint test

By simply moving the text on the dashboard (for example, using a written sheet of paper), it was possible for the subject's neck to move and thus cover the entire neck CROM. At the end of each test, subjects graded their perception of comfort with a score.

3.4.3 Shoulder joint test

The shoulder test was performed by preparing a large vertical crossword puzzle with the squares being filled with unordered numbers (written on movable paper sheets). It was previously shown that the paper sheet (on the wall) allowed subjects to move their shoulders into the CROM; the position was identified using the anthropometric measures for each subject and then simulating its movements using DELMIA™ software.

Fig. 3.3: Shoulder joint test

In the shoulder test, subjects were asked to execute the following operations (Fig. 3.3):

1) Stand up in front of the dashboard;
2) Direct their arm to point their index finger towards a number;
3) Completely extend the arm (180° elbow) when pointing to the numbers.

These operations allowed to test the shoulder in several positions and measure the angles of abduction and adduction. Subjects were asked to score the comfort of each position.

Subsequently, subjects were asked to score the level of comfort when the arm was positioned along the body (shoulder extension equal to 0°) and when the hand reached a handgrip located behind the body with shoulder extension being equal to −45°.

3.4.4 Elbow joint test

Two different tests were performed to evaluate the comfort level of the elbow in the CROM because two DOFs were taken into account: flexion/extension and prono-supination.

Fig. 3.4: Elbow joint - Flexion/Extension test

Fig. 3.5: Elbow joint - Prono-Supination test

The first test used a target that was printed on a virtual sheet (Fig. 3.4) and moved on the dashboard. Using their index finger, subjects had to follow the target with a blocked wrist and hand, moving only the elbow joint. In this way, the entire angular field of movement of the elbow was tested. The second test used a leverage made by a vertical beam hinged on a cylinder with a bearing (Fig. 3.5). Subjects had to grasp the beam and rotate it using only the forearm. Comfort associated with an angular position was evaluated by blocking the beam and asking subjects about their perceived comfort.

3.4.5 Wrist joint test

Two different tests were performed to evaluate the comfort level of the wrist in the CROM because two DOFs were taken into account: flexion/extension and radio-ulnar deviation (Figs. 3.6 and 3.7).

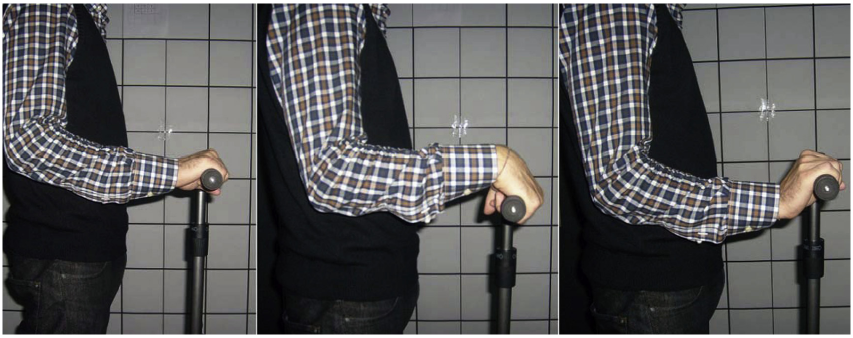


Fig. 3.6: Wrist joint - Flexion/Extension test

Fig. 3.7: Wrist joint – Radio-Ulnar Deviation test

Both tests used the same leverage as in the elbow tests. Subjects had to grasp a beam and rotate it using only the wrist joint. Comfort associated with an angular position was then evaluated by blocking the beam and asking subjects about their perceived comfort.

3.5 Results

Experimental data were processed using a NN whose output was the curves representing comfort values with regard to the joint angles for each human joint. The NN was required to produce a high number of points for the ROM domain of each joint. An example of this process, for elbow flexion/extension, is shown in Fig. 3.8.

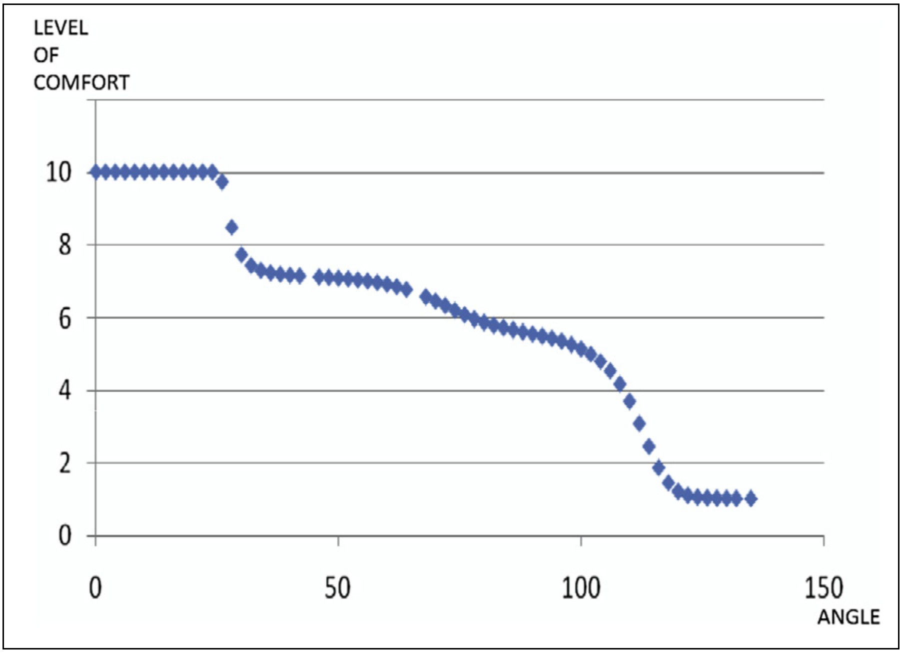


Fig. 3.8: Example of output of NN run: Elbow – Flexion/Extension.

Comfort level curves were determined for each human joint. When a posture is analysed, each joint angle corresponds to a comfort value. All joint values can be evaluated using the curve data and then combined to define an index to represent the global comfort for a determined posture. Each posture can be evaluated exactly as it is defined, that is, as a combination of human joint positions and angles.

The following Figures (3.9 to 3.12) depict all of the comfort curves:

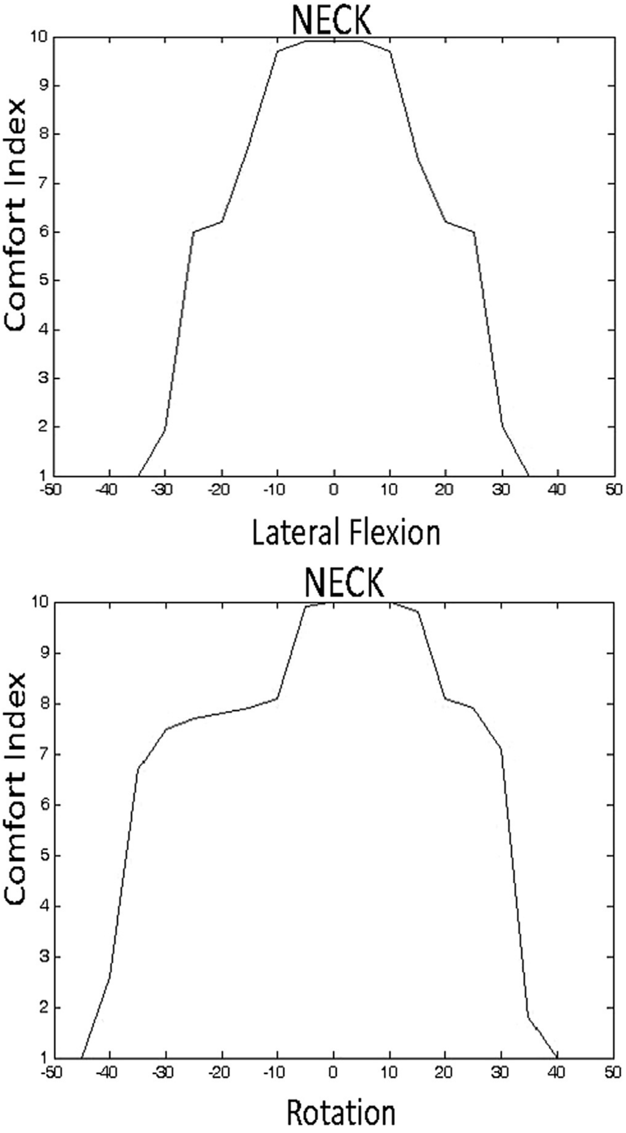


Fig. 3.9: Neck's Lateral flexion and Rotation Comfort curve

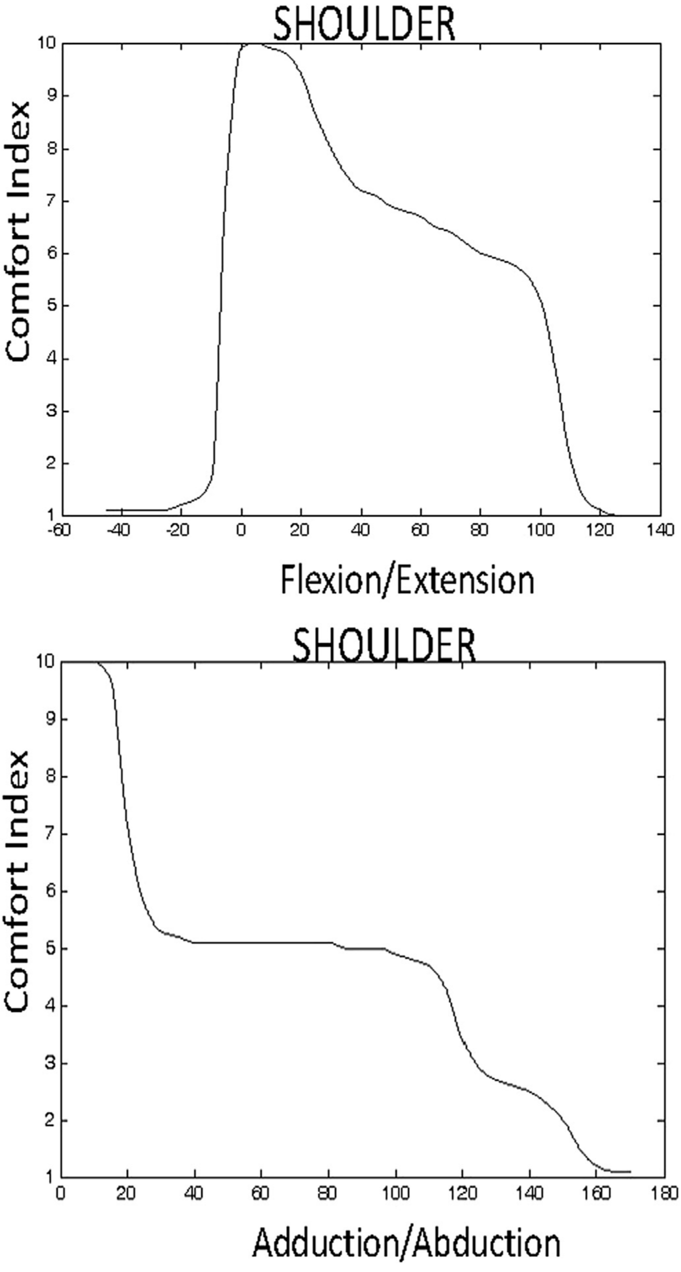


Fig. 3.10: Shoulder's Flexion/Extension and Abd/Adduction Comfort curves

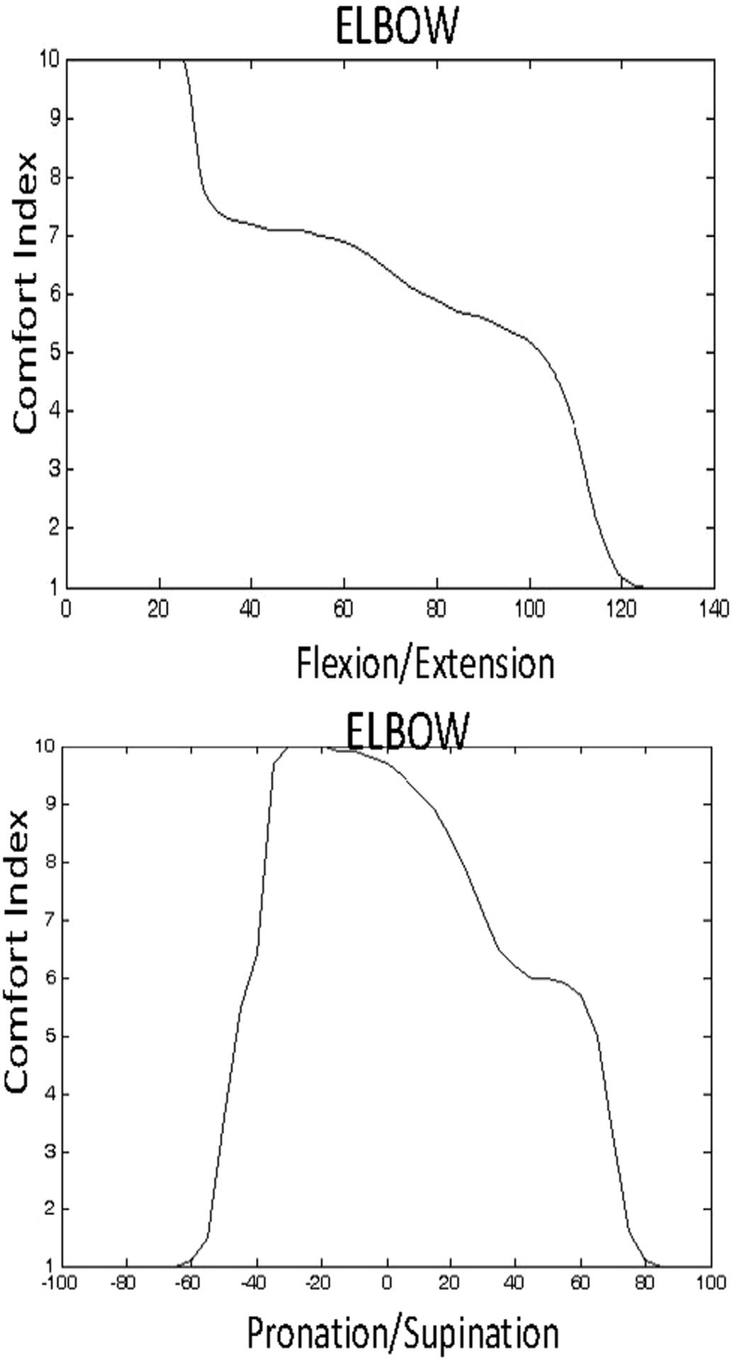


Fig. 3.11: Elbow’s Flexion/Extension and Prono/Supination Comfort curves

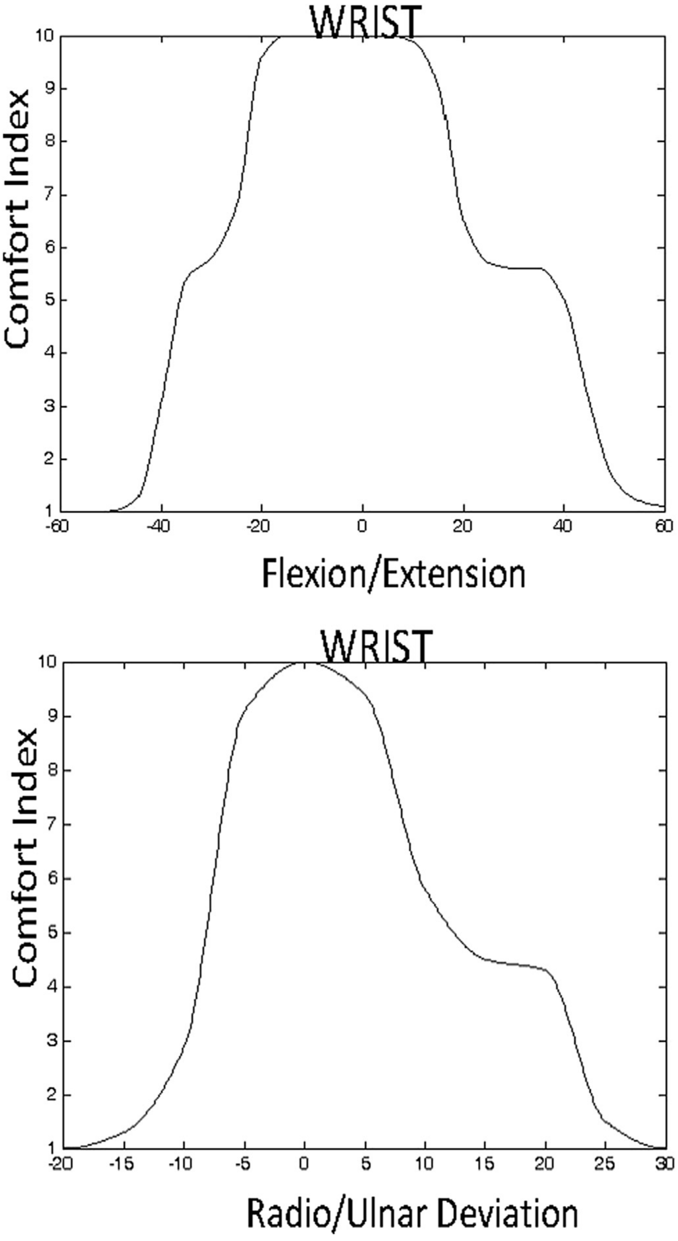


Fig. 3.12: Wrist's Flexion/Extension and Radio/Ulnar Deviation Comfort curves

A global comfort index can be defined as context-sensitive using different combination rules, the most common being the minimum, maximum, arithmetic/weighted mean, geometric mean, and sum. The minimum rule is applied to evaluate the comfort requirements that must be satisfied; it assigns a minimum score to the posture. The maximum rule is especially applied when at least one of the comfort requirements must be satisfied; it assigns the maximum score to the posture. The arithmetic mean is used when comfort requirements interact with each other; it gives to the posture a score calculated as the weighted/non-weighted mean of several comfort scores. The geometric mean is applied when every value of the evaluated posture deteriorates the final perceived comfort. Finally, the sum can be used when the comfort values for all of the joints equally contribute to the final comfort score.

3.6 Dashboard/car-seat test case

This test was conducted on human postures when seated in a car in the driving position (hands on the steering wheel). Postural parameters (joint angles) were calculated using cameras from different perspectives and software Kinovea© to process the captured images [27]. In the following Figures (3.13 to 3.15), the reference lines (to take measurements) are underlined in green.

Fig. 3.13: First Driving Posture: car seat far from dashboard

Fig. 3.14: Second Driving Posture: car seat close to dashboard

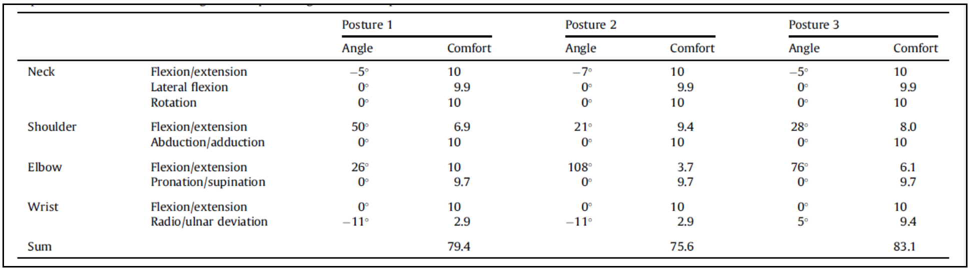
Fig. 3.15: Third Driving Posture: car seat in correct position

For this specific application, the following parameters are considered to be unimportant because they are very close to the "geometric zero" position:

- Neck: lateral flexion and rotation;
- Shoulder: abduction/adduction;
- Elbow: prono-supination;
- Wrist: flexion/extension.

In the experimental setup, three driving postures were selected. The first (Fig. 3.13) and second (Fig. 3.14) are incorrect driving postures, while the third (Fig. 3.15) is calibrated with respect to ergonomic suggestions given in the literature [28,29].

Test results are reported in Table 3.5. As observed, the examined postures result in quite variant comfort values. The use of a sum-like combination rule is due to the influence of all of the joint angles on the overall comfort perception for this specific test [30].



		Posture 1		Posture 2		Posture 3	
		Angle	Comfort	Angle	Comfort	Angle	Comfort
Neck	Flexion/extension	−5°	10	−7°	10	−5°	10
	Lateral flexion	0°	9.9	0°	9.9	0°	9.9
	Rotation	0°	10	0°	10	0°	10
Shoulder	Flexion/extension	50°	6.9	21°	9.4	28°	8.0
	Abduction/adduction	0°	10	0°	10	0°	10
Elbow	Flexion/extension	26°	10	108°	3.7	76°	6.1
	Pronation/supination	0°	9.7	0°	9.7	0°	9.7
Wrist	Flexion/extension	0°	10	0°	10	0°	10
	Radio/ulnar deviation	−11°	2.9	−11°	2.9	5°	9.4
Sum			79.4		75.6		83.1

Table 3.5: Experimental results when driving a car: acquired angles and correspondent comfort evaluation

The analysis of the first experimental setup (Fig. 3.13) shows a driver whose body is outstretched on the driving seat, with arms and legs stretched and the hip joints at an obtuse angle. This posture seems to be comfortable in terms of comfort perception, but it implies wide joint angles as each joint is far from a comfortable position. Evidently, the experimental setup is opportunely scaled towards the human percentile.

The analysis of the second experimental setup (Fig. 3.14) shows a driver whose body is curled up; few would agree that this posture is comfortable, but some people (i.e., those with poor eyesight) assume this posture. It is evident that the elbow flexion/extension value heavily affects overall comfort.

Finally, the analysis of the third experimental setup (Fig. 3.15) shows the optimal comfort values for the examined postures. The posture assumed by the tester seems to be comfortable and safe while driving (movement analysis is yet to be done). In this case, the comfort score is higher than in the other two.

3.7 Discussion

The developed comfort evaluation method can represent a useful support when designing and optimising HMI and work environments.

The most important characteristics of this method are its accuracy and ease of use. It can be applied to several different design contexts and used to support the decision-making steps in industrial projects. The integration of this method into digital human modelling (DHM) software for ergonomic/comfort application may enhance product and process prototyping in a computer-aided design (CAD) and computer-aided engineering environment, thus providing designers with a powerful instrument to preventively evaluate the comfort level of an HMI.

The results of this study only concern the upper limbs, but the research methodology can be applied to the lower limbs and torso. The proposed method can be applied in all cases on which load factors can be neglected (for example, as specified in ISO 11228 normative or in NIOSH method); this limitation represents a challenge for future works.

Future avenues of development should aim to define several parameters and factors that can be applied to comfort results (derived from curves) while taking into account the following:

- Gravitational effect (using the gravity-assisted point from the LUBA method);
- Arm support (e.g., headrest, armrest, or other rest surface);
- Postural equilibrium (weight distribution and operative spatial conditions);
- Handhold type;
- Frequency of repetitive actions;
- Time in the same posture;
- Muscular fatigue due to the applied loads.

Some of these factors have yet to be considered in experimental tests, although they were evaluated empirically; one of the main research group target is the development of a methodology to objectify these factors.

3.8 Conclusions

An extensive experimental survey on comfort perception was performed to determine the correlation between comfort perception and biomechanics parameters for several well-defined postures.

The use of photographic data acquisition, the RRP concept, and NN allowed to define and build comfort curves for each DOF of human upper limb joints. The obtained comfort curves are regular and do not show any discontinuity. These curves were then combined to define the new quantitative method for the evaluation of comfort perception based on human posture —the main result of this work— with the results verified in a dashboard and car seat test case. In this test case, the joints' comfort values have been combined with a "sum-like combination rule" after the analysis of the specific test [30]; nevertheless, other combination rules can be investigated, adjusted and correlated to specific case.

Some of the curves are not symmetric because of:

1) The presence of gravity force;
2) The interaction with other human body parts leading to the interference of other joint movements (e.g., the interference of the body with the arms/shoulder adduction/abduction);
3) The natural limits of joint movements (i.e., movement of the elbow).

The proposed method appears to work very well, although it was only tested under the following boundary conditions:

- Subjects were in a standing or seated position (no intermediate positions were tested);
- Arms and legs were free from constraints and footholds;
- All tested positions were evaluated without applied loads.

The results were subsequently used to develop a Comfort Manikin known as CaMAN®, to be used in a CAD or DHM environment.

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Chapter 4

The role of expectation in comfort perception: the mattresses’ evaluation experience

4 The role of expectation in comfort perception: the mattresses' evaluation experience

4.1 Summary

What are the new trends in research for comfort evaluation and the objective and predictive techniques for quantifying and qualifying comfort perception by humans? This chapter has attempted to answer this question in a wide literature review, whereby it is possible to highlight many partial aspects that have been studied successfully. Just a few researchers [1–3] have studied the problem of comfort perception and evaluation under a wider point of view. Nevertheless, some aspects seem not to have yet been taken into account. As reported in the General introduction, Naddeo et al. extended the Vink–Hallbeck model to build a comfort perception/evaluation matrix in which four kinds of comfort related to different humans' perception were studied and linked to the whole environment's characteristics. In the resultant perception-scheme and in the proposed "fusion rule" (for different kinds of perceived comfort/discomfort), one aspect that played a fundamental role in the final comfort/discomfort perception/evaluation was expectation. Expectation due to preconceived data (acquired or formed in the users' minds) and the influence of the working environment, can act in terms of additive or subtractive factor in the comfort experience by altering the final comfort/discomfort perception and changing the subjective comfort/discomfort evaluation.

This chapter presents the results of expectation influence analysis on comfort evaluation. Using the placebo effect, authors conducted a wide experimental test with a wide sample of users, asking them to use and evaluate two identical mattresses that were dressed and described as two different products (the first one as a very cheap mattress and the second one as a high-level and expensive mattress). Differences between subjective evaluations have been statistically processed and correlated to anthropometric parameters to individuate and understand the role of expectation.

4.2 Introduction and state of art

As explained in chapter two, Comfort and Discomfort matter has been developed and deployed in many aspects that have been studied both for research purposes and for industrial purposes. ISO 11228 standards provide to companies a good reference, in terms of ergonomics and comfort, for evaluating postural ergonomics in load push/pull, manual lifting and carrying of loads, as well as for repetitive actions and defining a "postural load index" that represents the ergonomics level of an examined posture [4,5]. Several methods can be used for assessing ergonomics performances and comfort levels but, as resulted from a wide bibliographic research, the perceived level of comfort/discomfort is still an open issue. In Vink-Hallbeck model (2012) and in Naddeo et al. one (2014), shown in Fig. 4.1, the factors that are involved in (dis)comfort perception have to be studied also taking into account expectations (E) and perception modification due to testing devices (Naddeo, 2014). In [3], the role of expectations has been viewed as a modifier (additive or subtractive) both in comfort and in discomfort formulas. Just a few papers over the last two decades have dealt with expectations by analysing the correlation among them and other parameters involved in comfort/discomfort evaluation. Most of them deal with thermal comfort perception and expectation inside different types of buildings. In [6], thermal comfort inside private buildings has been studied to understand the effects of comfort perception on energy demand and on two different strategies for demand-management. One of the main results about expectation is that thermal and overall comfort perception, due to internal climate control, is affected more by psychological effect than by physiological effect; in comfort perception, expectation plays a relevant role in the case of active control of environment parameters (temperature, humidity, and aeration) while is less important in the case of passive control of environmental data. In both cases, physiological and psychological effects are aligned.

A similar experimental data analysis, made in two different buildings in Australia, was conducted by Deuble [7]; the conclusions suggested that the expectations affect the perception of comfort and are more important in the comfort evaluation when thermal control of environment is done directly by the subject. In the case of passive control, the study shows little influence of expectation on overall perceived comfort.

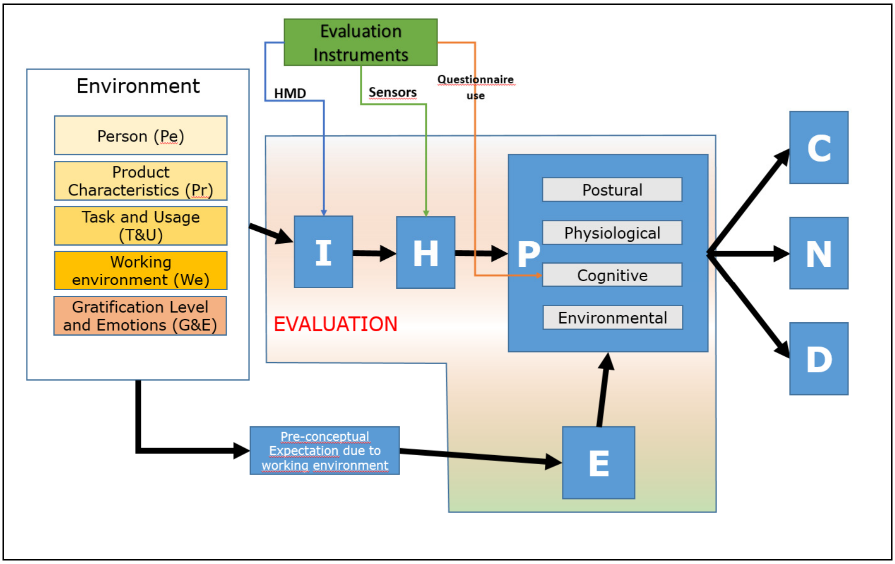


Fig. 4.1: Cappetti and Naddeo comfort/discomfort perception model

In [8], a definition of comfort was given: A passive provision of comfort is perceived as an absence of discomfort, while an active provision of comfort is perceived as a state of well-being. Due to this definition, expectation has a positive influence on comfort only in those environments in which the subject can control the thermal condition. This effect has been demonstrated also by placebo thermostats, by which (even if nothing changes) the subject believes they have the thermal control of the environment. In [9], a critical review about the norms used to certify the public thermal environments has been studied. In the study, the role of expectation has been analysed as a cultural- or country- dependent parameter. Brown and Cole [10] underlined that knowledge and control can affect the comfort perception. Among several parameters that can affect the comfort perception, three seem to be the most important: prior experience, personal knowledge about the comfort experience, and the expectation of perceivable comfort. The study was performed on the thermal condition in two different kinds of buildings in Canada. In this study, researchers showed that the perceived quality is the difference between the real quality of the service and the expected one; that expectation plays a role in shaping the direction and magnitude of influence on perception as a directional amplifier. In the study of Winzen and Marggraf-Micheel [11], the effect of preference and expectation on comfort evaluation in an aircraft cabin was performed. In that study, expectation was defined as the “anticipation of a future event,” and the authors hypothesized that people generally chose the option they expect would have the greatest value. To understand the effect of expectation on the perceived comfort, three aspects are taken into account by authors: how important the climate situation is for an individual passenger, how difficult he or she is to please (levels of demands), if expectations regarding the climate situation about to be encountered are either positive or negative. Several scenarios have been investigated using the placebo effect to better understand the correlation between comfort and expectation, and statistical analyses have been performed on obtained results. The main results of that paper were that, in the case of an objectively uncomfortable situation, a higher expectation has the effect of diminishing the overall comfort evaluation; in an objectively comfortable situation, a higher expectation has the effect of improving the overall comfort evaluation. Two other relevant results of this study were that “the more important the climate situation was to the subjects, the less comfortable it was judged to be with regard to all the climate parameters tested” and that “for subjects who had high expectations or were discerning with regard to the climate situation, there was a rather large disparity between their expectations and the reality they encountered. The climate situation was thus rated as being less comfortable. Subjects who had positive expectations experienced rather small discrepancies and assimilation occurred; the climate situation was rated as being more positive” the “assimilation contrast theory” [12] seems to provide a basis for interpreting that.

Generally, all cited papers recognize expectation as a fundamental role in modifying the real comfort perception.

The main target of this study was to understand the mechanism of expectation influence on overall comfort; to do that, an experimental test that used the placebo effect was prepared. The study was conducted on “perceived comfort while using a mattress in a short-time rest experiment. Authors asked the subject to test two “described as different” mattresses in a 15-minute rest-experiment and to evaluate them in terms of perceived comfort. Because the mattresses are, in reality, identical, the difference between subjective comfort evaluations are due only to different expectations of the subjects. The secondary target was to understand if the expectation influence can be correlated to anthropometric data of subjects and if the different parts of the body concur in different ways to the expectation influence on overall perceived comfort. Knowledge and cultural background influences were not analysed because the statistical sample was extracted from a population that has similar habits and cultural background (students of a second-year Master of Engineering). Environmental parameters were not analysed because all tests were performed in a temperature/humidity/ventilation constant situation.

4.3 Materials and Methods

The study was conducted in the Design and Methods laboratory at University of Salerno. Two identical mattresses, manufactured by Rinaldi Group S.r.l. (a large mattress manufacturer company in Giffoni Valle Piana (SA) – Italy) were used. The mattresses were placed in a closed environment, fully thermally controlled, with very little fluctuation of temperature and humidity (about ±2%) and with soft, indirect air circulation. During the tests, lights were switched off to simulate a short rest-time (15 minutes) in silent conditions.

4.3.1 Sample

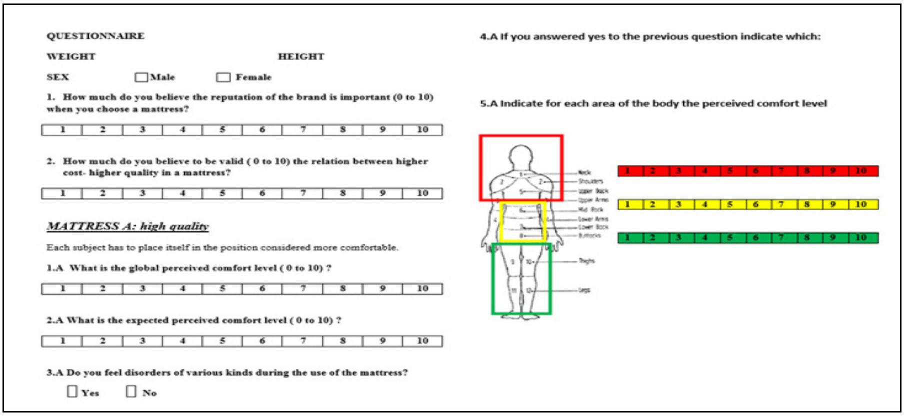
The recruitment of participants was undertaken among the students of the last year of MD Courses of Mechanical and Management Engineering at the University of Salerno.

The sample can be considered homogenous: The students' ages were between 23 and 25 years. Because the subjects attended the same faculty and all passed the same exam (or fulfilled the requirements) to attend the MD at University of Salerno, it was assessed that all participants had the same cultural profile and had been selected over the years for their preparation and inclination toward the sciences. Most of them came from the same geographical area, with the same yearly weather conditions; therefore, habits about cold/warm sensitivity might not have affected their judgment. The sample was clustered in terms of age, gender, anthropometric characteristics (height, weight, and percentile). Subjects were asked to wear standardized clothes (no shoes, long sleeves, and trousers) and not to use any kind of cushion or blankets because the inside-laboratory temperature was good for resting (20°C with 50% humidity).

4.3.2 Instruments, materials and data acquisition

The mattress used for the test was the SHIRLEY model of Valflex’s product line; it was an anatomical multi-foam mattress in which three different layers were combined: the top layer was made of Multi Foam Fresh Gel, the middle layer was Mind Foam Memory Effect with massaging effect, and the lower layer was made of Technocell AquPur high-density with open cells, which ensured a firm support. The mattress’ height was 22 cm, 80 cm wide by 188 cm in length. The mattress was covered by an elastic cover made of cotton and polyamide that hid the internal characteristics of the mattress and contributed to distribute the subject-weight in a proper manner along the mattress fibres. A thin elastin (for hygienic purposes) also covered both mattresses (Fig. 4.3).

The chosen method for data acquisition was a questionnaire. This questionnaire was prepared to acquire personal information and ratings about expected and perceived comfort during resting-time on the mattresses. The same questionnaire was used for rating the “low quality” and the “high quality” mattress. This questionnaire was drawn up by taking inspiration from some scientific papers [13-15] and customized for the specific application.



QUESTIONNAIRE

WEIGHT HEIGHT

SEX ☐ Male ☐ Female

1. How much do you believe the reputation of the brand is important (0 to 10) when you choose a mattress?

1	2	3	4	5	6	7	8	9	10

2. How much do you believe to be valid (0 to 10) the relation between higher cost- higher quality in a mattress?

1	2	3	4	5	6	7	8	9	10

MATTRESS A: high quality

Each subject has to place itself in the position considered more comfortable.

1.A What is the global perceived comfort level (0 to 10) ?

1	2	3	4	5	6	7	8	9	10

2.A What is the expected perceived comfort level (0 to 10) ?

1	2	3	4	5	6	7	8	9	10

3.A Do you feel disorders of various kinds during the use of the mattress?

☐ Yes ☐ No

4.A If you answered yes to the previous question indicate which:

5.A Indicate for each area of the body the perceived comfort level

1	2	3	4	5	6	7	8	9	10
1	2	3	4	5	6	7	8	9	10
1	2	3	4	5	6	7	8	9	10

Fig. 4.2. Questionnaire

The mattresses used were the same, but to exploit the power of placebo effect for understanding expectation in comfort perception, it was reported to the subjects that the mattresses were different from each other: Mattress A was a high quality mattress having a higher price; Mattress B was a low quality mattress and cheaper than A.

As seen in the questionnaire (Fig. 4.2), the first part of the questionnaire was not related to the mattress' characteristics but reported general questions and data about the subject's characteristics and preferences.

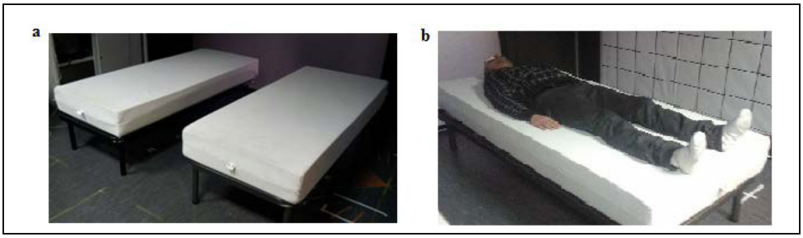


Fig. 4.3: (a) Setup in "Design and Methods" laboratory at University of Salerno; (b) example of testing

The first two questions highlighted whether the reputation of the brand was important to the subject, how it affected general expectations of the product and the importance of value for money. This information was useful to understand if, how, and what may affect the expected comfort level. In the second part of the questionnaire, there are five questions about comfort; the authors asked the subjects the level of global perceived and expected comfort during the test, the level of the perceived comfort for different parts of the body and, in case of disorders suffered, what they are.

4.3.3 Procedure

As stated previously, the test was performed in a closed and bounded laboratory (Fig. 4.3a), isolated from other environments and from external light. The subjects were invited, in set of two, into the laboratory, and the procedure was explained to them. They were invited to answer the first part of the questionnaire before beginning the session. Each subject was told that Mattress A was different from Mattress B and that he or she had to spend 15 minutes on Mattress A and then answer the questionnaire for Mattress A. After that, he or she spent 15 minutes on Mattress B and then had to answer the questionnaire for Mattress B (Fig. 4.3b).

4.3.4 Data processing

Data from 41 subjects (12 female and 29 male) were considered for the analysis of questionnaires. Arithmetic means of scores and standard deviations about perceived and expected comfort were calculated to compare the two mattresses' ratings. For each part of the body, a multivariate analysis was performed to determine possible correlations among the variables. One-way ANOVA was performed to determine which factor was discriminating for the variables under study. A Frequency analysis was also performed for analysing the effect of expectations on perceived (dis)comfort.

4.4 Results

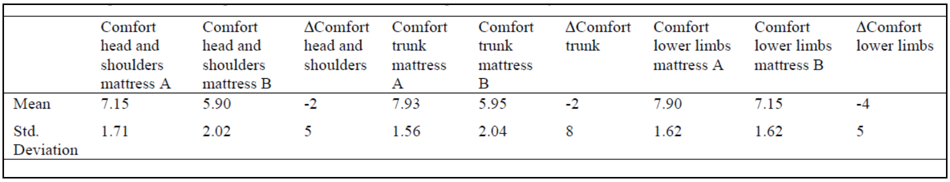
Through the analysis of questionnaires, the following data were collected:

- Subjective level of perceived comfort expressed on a scale of 0 to 10, with 10 being best.
- Subjective level of expected comfort expressed on a scale of 0 to 10, with 10 being best.
- Comments on own attitudes about brand awareness, product price, quality and their influence on own choice.

Data from 41 subjects (12 female and 29 male) were considered for the analysis of questionnaires. Arithmetic means of scores about perceived and expected comfort were calculated to compare the two mattresses' ratings.

In a first step, frequency analyses were used to identify differences between the independent variables. The mean of perceived comfort for Mattress A was 7.85 (SD = 1.01) and for Mattress B was 6.41 (SD = 1.41); it confirmed that the comfort was perceived as being higher on Mattress A, suggesting that subjects perceived the two mattresses as significantly different to each other (▯Comfort = 1.44). The differences between the perceived comfort on Mattress A and the perceived comfort on Mattress B were also confirmed (shown in Table 2) by the comfort ratings that subjects gave to the different parts of their own body, as asked in the questionnaire. Notable difference was found, especially for the trunk: the subjects, who perceived the two mattresses to be different, noticed a major difference in the area of the trunk.

The mean of expected comfort for Mattress A was 8.51 (SD = 1.10) and for Mattress B was 5.90 (SD = 1.26): it shows how expectations influence the subjects' judgment: subjects expected higher comfort on the mattress that belonged to the high brand and less comfort on the mattress belonging to the low brand (ΔExpected-Comfort = 2.61). One-way ANOVA was performed to determine whether gender was a discriminating factor for the variables under study: None of the factors resulted in statistically different mean values between males and females. The first two questions of the questionnaire -subjects had to give a judgment as to the importance of brand and cost of a product in relation to the level of product's quality- were analysed.



	Comfort head and shoulders mattress A	Comfort head and shoulders mattress B	ΔComfort head and shoulders	Comfort trunk mattress A	Comfort trunk mattress B	ΔComfort trunk	Comfort lower limbs mattress A	Comfort lower limbs mattress B	ΔComfort lower limbs
Mean	7.15	5.90	-2	7.93	5.95	-2	7.90	7.15	-4
Std. Deviation	1.71	2.02	5	1.56	2.04	8	1.62	1.62	5

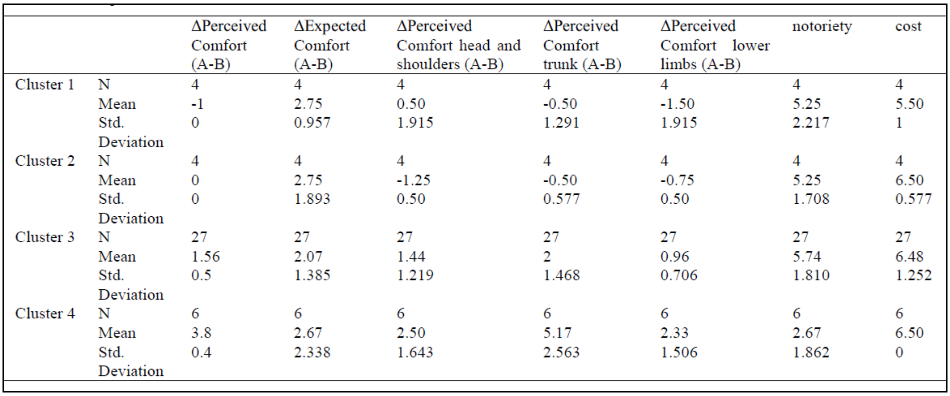
Table 4.1: Descriptive statistics of perceived comfort for the several parts of the body

Analyses of correlations demonstrated that the brand was correlated only with the perceived comfort on Mattress B (Pearson correlation is significant at the 0.05 level); this demonstrated that people that gave a higher value to cost and brand but not necessarily a higher value when evaluating Mattress A. This result is in contrast to what had been assessed in Winzen and Marggraf-Micheel [11], and the subjects' behaviour can be explained through their will to not show consumer behaviour for moral reasons. It has to be deeper.

Finally, a large multivariate analysis was performed to verify possible correlations among the variables. The statistical analysis software SPSS rel.13 was used to perform these analyses. Pearson correlation coefficients were calculated to determine the strength of the relationships among all the variables. The Pearson index revealed high correlation among the considered variables. However, the more significant correlations were the ones between the PerceivedComfort, related to Mattress A, and the PerceivedComfort, related to Mattress B (positive correlation is significant at the 0.01 level), the correlation between the ΔExpectedComfort and the ΔComfort related to Mattress A (negative correlation is significant at the 0.01 level), and the correlation between the ΔExpectedComfort and ΔComfort related to Mattress B (positive correlation is significant at the 0.01 level).

A wider analysis was performed by dividing the tested sample into clusters and by considering, as a clustering variable, the ΔComfort perceived.

According to this clustering variable, people were divided into 4 clusters (N = number of subjects). The first group perceived more comfort on Mattress B (presumed low quality mattress); the second group perceived the same comfort on both mattresses, and the groups 3 and 4 perceived more comfort on Mattress A (presumed high quality mattress) with two levels of Comfort. The results of this clustering operation are shown in Table 2, in which, it is possible to see how the other analysed variables are represented.



		ΔPerceived Comfort (A-B)	ΔExpected Comfort (A-B)	ΔPerceived Comfort head and shoulders (A-B)	ΔPerceived Comfort trunk (A-B)	ΔPerceived Comfort lower limbs (A-B)	notoriety	cost
Cluster 1	N	4	4	4	4	4	4	4
	Mean	-1	2.75	0.50	-0.50	-1.50	5.25	5.50
	Std. Deviation	0	0.957	1.915	1.291	1.915	2.217	1
Cluster 2	N	4	4	4	4	4	4	4
	Mean	0	2.75	-1.25	-0.50	-0.75	5.25	6.50
	Std. Deviation	0	1.893	0.50	0.577	0.50	1.708	0.577
Cluster 3	N	27	27	27	27	27	27	27
	Mean	1.56	2.07	1.44	2	0.96	5.74	6.48
	Std. Deviation	0.5	1.385	1.219	1.468	0.706	1.810	1.252
Cluster 4	N	6	6	6	6	6	6	6
	Mean	3.8	2.67	2.50	5.17	2.33	2.67	6.50
	Std. Deviation	0.4	2.338	1.643	2.563	1.506	1.862	0

Table 4.2: Descriptive statistics of the four defined clusters

For all clusters, people expected a greater comfort on the mattress belonging to the presumed higher quality set.

Cluster 1 (N = 4) perceived a higher comfort on the lower range mattress, despite their expectation of more comfort on Mattress A. In this cluster, the people noticed the differences, especially for the legs and trunk.

Cluster 2 (N = 4) expected more comfort on the mattress of presumed higher quality but, after the test, the subjects decided that the two mattresses were equal. Despite that, subjects judging the perceived comfort in the different parts of the body gave a lower score to the mattress of presumed lower quality.

Subjects who belong to cluster 3 (N = 27) and 4 (N = 6) said that the two mattresses were different. Both groups expected greater comfort on Mattress A and, after the test, confirmed that they were more comfortable on Mattress A. In particular, the results for clusters 3 and 4 showed that the increase of the expected comfort corresponded both to an increase of the perceived overall comfort and comfort of different parts of the body.

4.5 Conclusions

The aim of this study was to determine the correlation between the expected comfort and the real perceived comfort during the use of a product by the customer. Expectation is a factor related to the environment, and it is strongly influenced by cultural/experience background of the analysed subjects [3]. In this case, the authors wanted to determine if the level of expected comfort was also affected by the notoriety/cost of a mattress. The analysis of the results has showed that the level of expected comfort related to Mattress A was higher than that of Mattress B, for the entire sample.

The Perceived comfort was greater for Mattress A in most cases [N = 33]. Four subjects said that the Comfort Perceived on Mattress B was higher than that of Mattress A. Four subjects perceived the same comfort level on both mattresses, despite the fact that the subjects who judged the perceived comfort in the different parts of the body gave a lower score to the mattress of presumed lower quality. Therefore, in this case, people did not respond to the other questions of the questionnaire considering the value given to the perceived comfort but rather considering the value given to the expected comfort.

One-way ANOVA confirmed that the variables under study did not result in statistically significant different mean values in relation to the subjects' gender. The correlation analyses have shown that the Perceived Comfort of Mattress A and the Perceived Comfort of Mattress B were linked to each other.

The Pearson index also revealed that an increase of the Expected Comfort implied a decrease in Comfort (difference between Expected and Perceived) related to Mattress A and an increase of Comfort (difference between Expected and Perceived) related to Mattress B. The frequency analysis showed that the Expectations affected the average value of Perceived Comfort with an effect of 18.3%.

The obtained results have confirmed what was assessed by the Naddeo et al. [3] model that showed an indirect correlation between the Expected Comfort and the Perceived Comfort: an increase of the Expected

Comfort implied a decrease of the Perceived one, and a decrease of the Expected Comfort implied an increase of the Perceived one.

In fact, for Mattress A, the average value of the expected comfort (Mean Expected Comfort = 8.51) was greater than the average value of the perceived comfort (Mean Perceived Comfort = 7.85), while for Mattress B, the average value of the expected comfort (Mean Expected Comfort = 5.90) was greater than the average value of the perceived comfort (Mean Perceived Comfort = 6.41).

4.6 Acknowledgement

Experimental tests were performed in the virtual reality laboratory (VRLab) of the Department of Industrial Engineering at the University of Salerno, Italy. Many thanks to the students of last year's mechanical and management engineering class (2015), who gave their time and patience in carrying out many hours of testing.

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Chapter 5

The effect of external and environmental factors on perceived comfort: the car-seat experience

5 The effect of external and environmental factors on perceived comfort: the car-seat experience

5.1 Summary

Today, the comfort and discomfort related to the automobile seat are widely studied. A previous work, published by this current study's authors [1], affirmed that the evaluation of the perceived comfort associated with the driving experience could not be performed by considering only the driver's seat. The authors offered a theoretical matrix to evaluate the comfort of car seats through identification of all involved aspects and the interactions with external factors inside the vehicle (personal, task and environment characteristics). To verify this hypothesis, a sample of subjects evaluated a car seat by interacting with it in five ways: interaction with the real prototype, presentation of a real prototype, photographic presentation of a real prototype, presentation of a 3D virtual digitized prototype, and interaction with the real prototype placed inside the car. The Kansei technique has been used as an evaluation tool to assess the individual and subjective emotional impressions of the car seat where all the senses of the consumer are involved. The results of the study show how the same object looks different if evaluated in different ways and the effects of external and environmental factors on the perceived comfort.

5.2 Introduction

5.2.1 Motivation

Thousands of people experience comfort or discomfort on their automobile seat daily, especially drivers on long trips. Comfort during the task of driving is a multifaceted phenomenon that is not exclusively related to the seat but to all elements that interact with the driver. All these elements can influence the driving experience's comfort and, in particular, the user's sensation of comfort about the seat. To demonstrate this hypothesis, the same seat was represented in different ways and in different environments and evaluated by a sample of subjects.

5.2.2 NC-Model

As shown in general introduction, Naddeo et al. [1] represented the comfort experience using a big matrix in which the comfort-related elements were classified and studied. According to the NC-model of perception, the experience of comfort/discomfort in a generic environment was represented by the logic sum of four main aspects that contribute to HMI description and classification: Person, Product Characteristics, Task and Usage, and Working Environment (see Fig. 5.1).

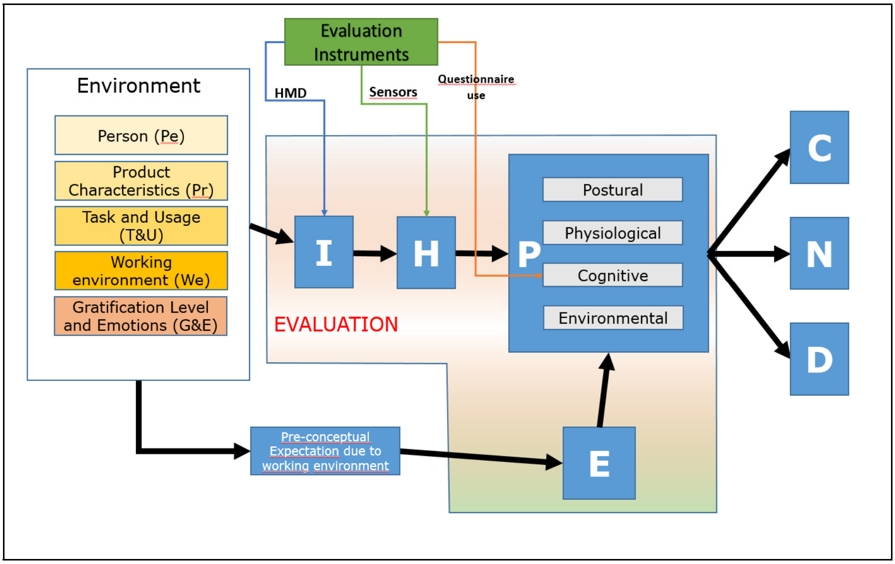

Fig. 5.1: NC-model of comfort perception

- Person (Pe): represents the human body's geometric and personal characteristics when involved in tasks;
- Product (Pr): represents all geometric and non-geometric characteristics of the elements that come into contact with the human body during task execution.
- Task/Usage (T): represents all the tasks or the uses that humans perform during HMI experience (kind of contact, kind of interaction);
- Working Environment (We): represents the set of parameters characterizing the space in which the person interacts.

The interaction (I) with an environment is caused by the contact (also nonphysical contact, such as a signal in the study of De Korte et al. [2] between the human and the product and its usage). This can result in internal human body effects (H), such as tactile sensations, body posture change, and muscle activation. The perceived effects (P) are influenced by the human body effects but also by expectations (E). These are interpreted as “comfortable” (C) or “you feel nothing” (N), or they can lead to “feelings of discomfort” (D) [3].

In the NC-model of perception, the working environment is directly connected to expectations. In the automotive field, expectations assume a central role in the personal car–driver experience. According to the authors, if the product has a particular design and therefore a higher cost than do other products, the users have higher expectations, thereby influencing the comfort perception [4].

An aspect that cannot be underestimated—it is always present when a comfort/discomfort evaluation is performed—also integrates this model: the perception modification due to experimental devices needed to evaluate comfort. For example, a head-mounted display (HMD) used for virtual reality (VR) applications in HMI evaluation can modify the postural comfort perception (Interaction – I); the use of markers/sensors on the naked body to perform pressure/temperature/movement data acquisition can change the physiological comfort perception (Human Body Effect – H); the use of the questionnaire can annoy the participants and directly modify their cognitive comfort perception (Perceived Effects – P).

Each element of the NC-model has been deployed and detailed. For each kind of interaction (I), one or more human body effects (H) have been found.

5.3 Driving model: Literature review helps build the NC-matrix model

Naddeo and Cappetti [1] have identified a suitable application of the matrix: the automobile seat, a sub-matrix in which all elements that influence a driver’s perception of comfort are considered (Fig. 5.2).

SEAT-COMFORT			
PHYSIOLOGICAL	*EMOTIONAL-COGNITIVE*	*ORGANIZATIONAL-ENVIROMENTAL*	*POSTURAL*

PERSONAL CHARACTERISTICS			
PHYSICAL CHARACTERISTICS			
Anthropometric measures			
(M)	(M)		(P)posture overload, muscle complaint
Physique (BMI)			
(P)localized blood-pressure, body temperature, heartrate, metabolism	(M)tiredness		(P)muscle effort, posture overload, muscle complaint
Physical problems			
(P)tactile sensation, localized blood-pressure, body temperature, heartrate	(M)work overload, tiredness		(P)muscle effort, posture overload, muscle complaint
PERSONAL DATA			
Gender			
(P)localized blood-pressure, body temperature, heartrate, metabolism	(P)		(P)
Age			
(P)tactile sensation, localized blood-pressure, body temperature, heartrate, metabolism	(P)lack of attention		(P)muscle effort
EXPECTATIONS			
Expectations			
(M)	(P)perceived safety, aggressiveness and irritability, stress		(M)
WORK/TASK CHARACTERISTICS			
WORKSTATION			
Posture: angles and joints			
(M)	(M)	(M)	(P)muscle effort, posture overload, muscle complaint
CHARACTERISTICS OF TOOLS/OBJECTS WITH WHICH A PERSON INTERACTS			
Shape			
(M)	(M)	(M)	(P)muscle effort, posture overload, muscle complaint
Customization of the workstation (sitting)			
(M)tactile sensation	(M)tiredness	(M)perceived safety	(P)muscle effort, posture overload, muscle complaint
WORKING ENVIRONMENTS' CHARACTERISTICS			
VISUAL WELL-BEING			
Colours			
(M)	(M)aggressiveness and irritability, tiredness, lack of attention	(P)	(M)
Odours			

(M)	(M)aggressiveness and irritability, lack of attention	(P)	(M)
AUDITIVE WELL-BEING			
Vibrations			
(M)	(M)work overload, safety, aggressiveness and irritability, tiredness, lack of attention	(P)	(P)muscle effort, posture overload, muscle complaint
THERMAL WELL-BEING			
Interface temperature			
(P)tactile sensation, localized blood-pressure, body temperature	(M)lack of attention	(M)	(M)
Thermal resistance of clothing			
(P)tactile sensation, localized blood-pressure, body temperature	(M)	(M)	(M)
Persistence in a thermal condition			
(P)tactile sensation, localized blood-pressure, body temperature, aggressiveness, nervousness	(M)aggressiveness and irritability, lack of attention	(M)level of perceived safety	(M)
Contact pressure			
(P)tactile sensation, localized blood-pressure	(M)	(M)	(M)
TOOLS AND INSTRUMENTS FOR COMFORT MEASURING			
Invasivity			
(M)	(M)aggressiveness and irritability, lack of attention	(M)	(M)
Tactile interference			
(M)tactile sensation, localized blood-pressure	(M)lack of attention	(M)	(M)
Restriction of movements			
(M)	(M)work overload, aggressiveness and irritability, tiredness, lack of attention	(M)	(M)muscle effort, posture overload, muscle complaint
Override of action/ position			
(M)	(M)perceived safety, aggressiveness and irritability, tiredness, lack of attention	(M)	(M)muscle effort, posture overload, muscle complaint

Fig. 5.2: Seat-comfort evaluation sub-matrix

According to the NC-model used to evaluate level of satisfaction, all the elements of Environment and the way in which they interact among themselves and with the driver have to be considered. It is necessary, therefore, to start from the sub-matrix of the seat's comfort and widen the horizon of evaluation.

If we hypothesize that the comfort inside a car is mostly related to the following factors: person, task and environment, we can schematize the comfort perception as in Fig. 5.3.

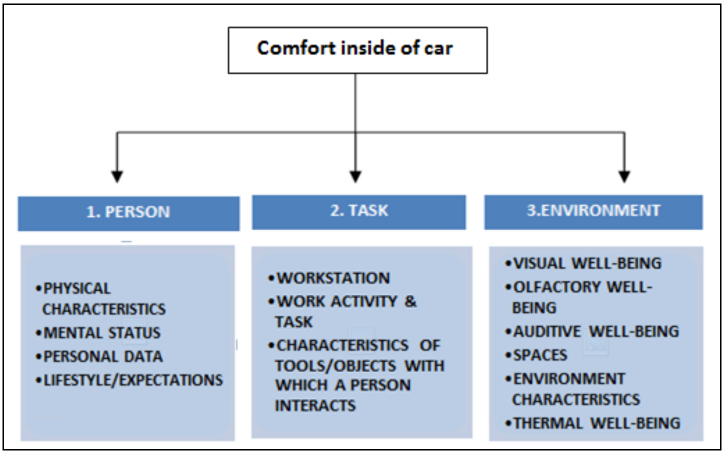

Fig. 5.3: Hypothesis of schematization of elements that influence comfort inside of a car

The class labelled "person" comprises personal characteristics; the physical characteristics that influence comfort include anthropometric measures (Reed et al. [5]; Kolich [6-8]; Fazlollahtabar [9]) and consequent postures (Naddeo et al. [10]) that are the starting point for dimensions, physique (BMI) [6], and physical problems. Mental status, personality and psychological conditions influence the level of tiredness, the level of attention, biomechanical loading (Nimbarte et al.[11]) and fatigue, shown as increments of the drivers' physiological and emotional discomfort levels (Gerald [12]).

Identifying the correlation between age and gender in regard to perceived level of comfort is difficult because people of the same gender and age can have different perceptions. However, it can be stated that with increasing age, the level of perceived safety differs and the level of attention decreases, as well as gender influences on muscle strain and sensitivity to noise and vibration (Dauris et al. [13]) (see Fig. 5.4).

PERSONAL CHARACTERISTICS			
PHYSIOLOGICAL	*EMOTIONAL-COGNITIVE*	*ORGANIZATIONAL-ENVIROMENTAL*	*POSTURAL*
PHYSICAL CHARACTERISTICS			
Anthropometric measures			
(M)	(M)		(P)posture overload, muscle complaint
Physique (BMI)			
(P)localized blood-pressure, body temperature, heartrate, metabolism	(M)tiredness		(P)muscle effort, posture overload, muscle complaint
Physical problems (chronic illness, trauma, and previous fractures)			
(P)tactile sensation, localized blood-pressure, body temperature, heartrate	(M)work overload, level of perceived tiredness		(P)muscle effort, posture overload, muscle complaint
MENTAL STATUS			
Personality			
(M)	(P)work overload, perceived safety, aggressiveness and irritability, level of perceived tiredness, stress, lack of attention		(M)
Psychological diseases (anxiety, stress)			
(M)body temperature, heartrate	(P)perceived safety, aggressiveness and irritability, tiredness, stress, lack of attention		(M)
PERSONAL DATA			
Gender			
(P)localized blood-pressure, body temperature, heartrate, metabolism	(P)		(P)
Age			
(P)tactile sensation, localized blood-pressure, body temperature, heartrate, metabolism	(P)lack of attention		(P)muscle effort
LIFESTYLE/EXPECTATIONS			
Lifestyle (diet, smoking, sports, sedentary lifestyle,.. .)			
(P)body temperature, heartrate, metabolism	(M)aggressiveness and irritability, lack of attention		(M)muscle effort
Expectations			
(M)	(P)level of perceived safety, aggressiveness and irritability, stress		(M)

Fig. 5.4: Comfort framework for Personal Characteristics related to comfort while driving

The class labelled “task” rates the characteristics of the workplace (in this case, the car cockpit), the characteristics of the performed activity and the characteristics of the tools that user utilizes during the task.

The first consequence of the workstation (generally a car seat with its dashboard) is the posture the user has to assume. Each articulation and range of postures/angles help define a comfortable position (Apostolico et al. [14]). In the driving environment of a car’s cockpit, postures differ due to the confined space (for legs, shoulders, feet, etc.), the visual demands of the task and the seat itself. An increase of muscular activation can have detrimental effects, such as excess muscle effort and posture overload.

During the driving task, the user needs to perform (with a certain frequency) a series of actions such as pressing buttons, turning the steering wheel and using pedals. The work activity aspects influencing comfort are evaluated by different indicators: type of loads and actuation, operating speed (Apostolico et al. [14]; Naddeo et al. [15]), an action’s frequency, rest–pause duration and frequency. The perception of comfort in every situation can be affected by duration of the task (Moore & Garg [16]; Kee & Karwowski [17]).

A posture that is comfortable for a time can become uncomfortable after a longer time. The same happens with the driving experience, especially linked to the seat (Vergara & Page [18]). Drivers tend to move more frequently when feeling discomfort, adjusting posture to improve the situation (Lee et al. [19]). Increased body pressure variables during driving were similar to whole body discomfort levels (Seoke et al. [20]).

For this model, defining the driver’s comfort level refers only to the seat. In literature, in fact, the seat’s geometry (Reed et al. [5]; Kolich [6], Apostolico et al. [14]), breathability and rigidity are considered the most important indexes of driver comfort. During the driving experience, the driver interfaces not only with the seat but also with a high number of other elements (steering wheel, pedals, knobs, etc.). Each element’s shape (Kuijt-Evers et al. [21]), position (Ellegast et al. [22]; Naddeo et al. [15]; Naddeo et al. [23]; Patrick et al. [24]; Lars et al. [25]) and orientation can make the vehicle cockpit more or less comfortable (Naddeo et al. [23]).

<table>
<tr><th colspan="4">WORK/TASK CHARACTERISTICS</th></tr>
<tr><td><i>PHYSIOLOGICAL</i></td><td><i>EMOTIONAL-COGNITIVE</i></td><td><i>ORGANIZATIONAL-ENVIROMENTAL</i></td><td><i>POSTURAL</i></td></tr>
<tr><td colspan="4">WORKSTATION</td></tr>
<tr><td colspan="4">Posture: angles and joints</td></tr>
</table>

(M)	(M)	(M)	(P)muscle effort, posture overload, muscle complaint
Individual safety equipment: overall dimensions and heaviness			
(M)tactile sensation, localized blood-pressure, body temperature	(M)perceived safety, lack of attention	(M)	(M)muscle effort, posture overload, muscle complaint
WORK ACTIVITY & TASK			
Type of loads and actuation (lifting, pulling, pushing)			
(M)localized blood-pressure, body temperature, heartrate	(M)level of perceived tiredness	(M)	(P)muscle effort, posture overload, muscle complaint
Operating speed			
(M)body temperature	(M)work overload, tiredness, stress	(P)	(M)muscle effort, posture overload, muscle complaint
Actions' frequency			
(M)body temperature	(M)work overload, tiredness, stress	(P)	(M)muscle effort, posture overload, muscle complaint
Rest-pause duration and frequency			
(M)	(M)work overload, perceived safety, aggressiveness and irritability, tiredness, stress, lack of attention	(P)	(M)muscle effort, posture overload, muscle complaint
Revel of precision			
(M)	(M) aggressiveness and irritability, tiredness, stress, lack of attention	(P)	(M)muscle effort, posture overload, muscle complaint
Time maintaining of the posture with and/or without loads			
(M)localized blood-pressure, body temperature, heartrate	(M)aggressiveness and irritability, tiredness	(M)	(P)muscle effort, posture overload, muscle complaint
Time and duration of work activity/tasks			
(M)	(M) aggressiveness, work overload, irritability, tiredness, stress, lack of attention	(P)	(M)muscle effort, posture overload, muscle complaint
Work-shifts			
(M)muscular exertion, aggressiveness, nervousness, tiredness	(M)work overload, perceived safety, aggressiveness and irritability, tiredness, lack of attention	(P)perceived safety	(M)
CHARACTERISTICS OF TOOLS/OBJECTS WITH WHICH A PERSON INTERACTS			
Shape			
(M)	(M)	(M)	(P)muscle effort, posture overload, muscle complaint
Weight			
(M)	(M)	(M)perceived safety	(P)muscle effort, posture overload, muscle complaint
Relative position between person and object/tool			

(M)	(M)	(M)perceived safety	(P)muscle effort, posture overload, muscle complaint
Frequency of lifting / pulling / pushing			
(M)heartrate, localized blood-pressure, body temperature	(P)tiredness	(M)	(M)muscle effort, posture overload, muscle complaint
Handling characteristics (grip, grasp, pinch, ….)			
(M)	(M)	(M)	(P)muscle effort, posture overload, muscle complaint
Customization of the workstation (sitting)			
(M)tactile sensation	(M)tiredness	(M)perceived safety	(P)muscle effort, posture overload, muscle complaint
Commands' layout			
(M)	(M)	(M)	(P)muscle effort, posture overload, muscle complaint

Fig. 5.5: Comfort framework for Work/Task Characteristics related to comfort driving

Today, people spend much more time in the car, especially those whose work involves driving for many hours (taxi driver, couriers, truck drivers, etc.) [26]; as such, the comfort of the car cockpit can be studied in ways similar to any work "environment." The colours of the interior, artificial lighting conditions, air quality and space are factors that influence the driver's perceived comfort.

Vibrations, for example, are one of the most important environmental aspects (Smith et al. [27]; Falou et al. [28]). The consequences of exposure to vibration can be a decrease in cognitive and postural comfort. Vibrations, in fact, result in an increase in the level of irritability, lack of attention and postural overload.

One issue involving improved functioning of the automobile are unpleasant smells due to materials used in the interior. Realizing this, Yoshio Yamada et al. [29] created advanced seat fabrics with high performance deodorant function that effectively controls the smell in the passenger compartment; in the matrix in Fig. 5.5, olfactory well-being is related to air quality and odours.

A study conducted by Ferrari S.p.A. in collaboration with the 2009 study by the Aerospace Engineering and Industrial Department of University of Pisa (Kartsiotis [30]) shows that car manufacturers pay great attention to studying thermal comfort and the impact it has on users and potential buyers. In the matrix, the thermal aspect is the consequence of influence factors such as humidity, temperature and thermal-resistance of clothes (D'ambrosio Alfano, & Liotti [31]). Ambient interior lighting has a dramatically growing relevance in the automotive industry. Ambient lighting provides indirect illumination of the passenger compartment in low-light settings, such as at night. It is important to provide a better orientation inside the car, an improved sense of spaciousness, as well as the impression of safety, value and comfort (Caberletti et al. [32]). In this study, aspects such as colours, luminance level, the combination of lighting materials and their reflection have been included in the matrix.

One of the most common evaluations on automobile seats is based on the interface pressure driver seat. Previous studies have shown that preferred pressure levels are different for different body parts as well as different anthropometric groups (Kolich [7]; Dunk & Callaghan [33]; Oudenhuijzen et al. [34]; Kyung et al. [35]). There are definite associations between interface pressure and seated discomfort and specific approaches are recommended to improve the driver's sitting experience i.e. decrease mean pressure at the buttocks and increase mean pressure on the back.

WORKING ENVIRONMENTS' CHARACTERISTICS			
PHYSIOLOGICAL	*EMOTIONAL-COGNITIVE*	*ORGANIZATIONAL-ENVIROMENTAL*	*POSTURAL*
VISUAL WELL-BEING			
Colours			
(M)	(M)aggressiveness and irritability, tiredness, lack of attention	(P)	(M)
Artificial lighting conditions			
(M)	(M)perceived safety, aggressiveness and irritability, tiredness	(P)perceived safety	(M)muscle complaint
Natural lighting conditions			
(M)	(M)aggressiveness and irritability, tiredness	(P)	(M)muscle complaint
Lights' reflection and refraction on walls and objects			
(M)	(M)aggressiveness and irritability, tiredness, lack of attention	(P)	(M)muscle complaint
OLFACTORY WELL-BEING			
Air quality			
(M)aggressiveness, nervousness	(M)aggressiveness and irritability	(P)	(M)
Odours			
(M)	(M)aggressiveness and irritability, lack of attention	(P)	(M)
AUDITIVE WELL-BEING			
Noises			

(M)	(M)perceived safety, aggressiveness and irritability, tiredness, lack of attention	(P)perceived safety	(M)
Vibrations			
(M)	(M)work overload, perceived safety, aggressiveness and irritability, tiredness, lack of attention	(P)	(P)muscle effort, posture overload, muscle complaint
SPACES			
Workspace			
(M)muscular exertion, aggressiveness, nervousness	(M)perceived safety, aggressiveness and irritability	(P)perceived safety	(M)muscle effort, posture overload, muscle complaint
Layout			
(M)	(M)	(P)perceived safety	(M)
ENVIROMENT CHARACTERISTICS			
Cleanliness			
(M)	(M)aggressiveness and irritability	(P)	(M)
Tidiness			
(M)	(M)work overload, aggressiveness and irritability	(P)	(M)
THERMAL WELL-BEING			
Air-temperature			
(M)body temperature, aggressiveness and nervousness	(M)aggressiveness and irritability, lack of attention	(P)perceived safety	(M)
Interface temperature			
(P)tactile sensation, localized blood-pressure, body temperature	(M)lack of attention	(M)	(M)
Humidity			
(M)localized blood-pressure	(M)	(P)	(M)
Thermal resistance of clothing			
(P)tactile sensation, localized blood-pressure, body temperature	(M)	(M)	(M)
Persistence in a thermal condition			
(P)tactile sensation, localized blood-pressure, body temperature, aggressiveness, nervousness	(M)aggressiveness and irritability, lack of attention	(M)perceived safety	(M)
Contact pressure			
(P)tactile sensation, localized blood-pressure	(M)	(M)	(M)
Air speed			
(M)body	(M)	(P)	(M)

temperature			

Fig. 5.6: Comfort-framework for Environment Characteristics related to comfort while driving

5.4 Materials and Methods

5.4.1 Participants

Twenty volunteers took part in this study. The participants were recruited from among students taking Mechanical, Management and Chemistry Engineering courses at the University of Salerno. In this way, the sample was quite homogenous. This aspect was necessary to ensure the investigation was valid and consistent. Students' ages were between 20 and 29 years. All were in possession of a valid driving license for at least three years.

5.4.2 Apparatus

A 2005 Ford Fiesta MY seat (see Fig. 5.7) was used for the test. The seat is characterized by the ability to adjust seat height and adjust the headrest. The seat has a fabric cover. After choosing the automobile seat, the research focused on the choice of different representations of the seat, which were not too expensive in terms of cost or time. Five ways to represent the car seat vis a vis human interaction have been chosen: physic interaction with the real prototype, presentation and observation only of real prototype, photographic presentation of real prototype, presentation of 3D virtual digitized prototype (the 3D virtual digitized prototype was realized by the reverse engineering method), and interaction with the real prototype placed inside the car.

Fig. 5.7: 2005 Ford Fiesta MY seat

5.4.3 Methods to acquire data

The Kansei Engineering methodology specializes in the translation of affective values into concrete product design parameters (Nakada [36]; Nagamachi [37]). To achieve this, Kansei Engineering uses semantic differential scales (SD-scales) as a central pillar. This special scale uses a 5-point scale to measure how a person feels about a certain object. The designers can then incorporate these data to improve the perception of the object. The questionnaire utilized during the test is shown in Fig. 5.8. The questionnaire was assembled based on indications from the NC-Matrix built from the mentioned review of past literature. Within the questionnaire, there are explicit questions on the perceived level of comfort as well as other questions relating to various indicators and facets of comfort on automobile seats considered in the literature (Zhang et al. [38]; Martin et al. [39]; Ebe & Griffin [40]; Desmet et al. [41]; Da Silva et al. [42]).

Comfortable	☐ ☐ ☐ ☐ ☐	Uncomfortable
Compact	☐ ☐ ☐ ☐ ☐	Not Compact
Elegant	☐ ☐ ☐ ☐ ☐	Not Elegant
Sober	☐ ☐ ☐ ☐ ☐	Excessive
Sport	☐ ☐ ☐ ☐ ☐	Tourist
It'll continue to like	☐ ☐ ☐ ☐ ☐	It will go to tire me
Pleasant	☐ ☐ ☐ ☐ ☐	Unpleasant
Gaudy	☐ ☐ ☐ ☐ ☐	Dull
Luxurious	☐ ☐ ☐ ☐ ☐	Cheap
Exciting	☐ ☐ ☐ ☐ ☐	Boring
Curved	☐ ☐ ☐ ☐ ☐	Linear
Design	☐ ☐ ☐ ☐ ☐	Rough
Usual	☐ ☐ ☐ ☐ ☐	Unusual
Refined	☐ ☐ ☐ ☐ ☐	Unrefined
Soft	☐ ☐ ☐ ☐ ☐	Hard
Relaxing	☐ ☐ ☐ ☐ ☐	Not Relaxing
Innovative	☐ ☐ ☐ ☐ ☐	Ordinary
Functional	☐ ☐ ☐ ☐ ☐	Decorative
Robust	☐ ☐ ☐ ☐ ☐	Easily broken
Pleasant	☐ ☐ ☐ ☐ ☐	Unpleasant
Good	☐ ☐ ☐ ☐ ☐	Not Good

Fig. 5.8: Questionnaire with Kansei terms

5.4.4 Procedure

During the test, participants were invited to interact with the different prototypes. During the physical interaction with the physical prototype, the participants placed themselves on the seat, allowing them to acquire information about the seat. In this case, the participants could evaluate the finish of the surfaces, the softness and the compactness of the coatings, as well as the level of comfort. The second test was evaluation of the physical prototype without any interaction with it and without giving any extra information. The participants could evaluate only the colours and the geometry of the seat. The third test was prototyping through photography. In this case, a short introduction was shown on the state-of-the-art automobile seat. The fourth type of interaction was a 3D presentation as a virtual digitized prototype (Fig. 5.9).

Fig. 5.9: Virtual prototype of the seat

Through this method, the participants experienced 3D vision of the object (similar to recent web-based car presentations). The final test was physical interaction with the automobile seat inside the car. In this case, the participants interacted with the seat; they could position the seat according to their preferences, interact with the other elements inside the car and listen the music (but without turning their attention from the seat). After each test, the subjects were required to complete the same questionnaire as the other prototypes to evaluate their comfort sensations. The aim of this study was to demonstrate that the same object, presented in different ways, results in different comfort sensations.

5.5 Results

After data acquisition, all the terms of the questionnaire were analysed. The results demonstrated that the highest score of comfort was obtained when the subjects evaluated the seat inside the car, simulating the driving experience for a few minutes (Fig. 5.10).

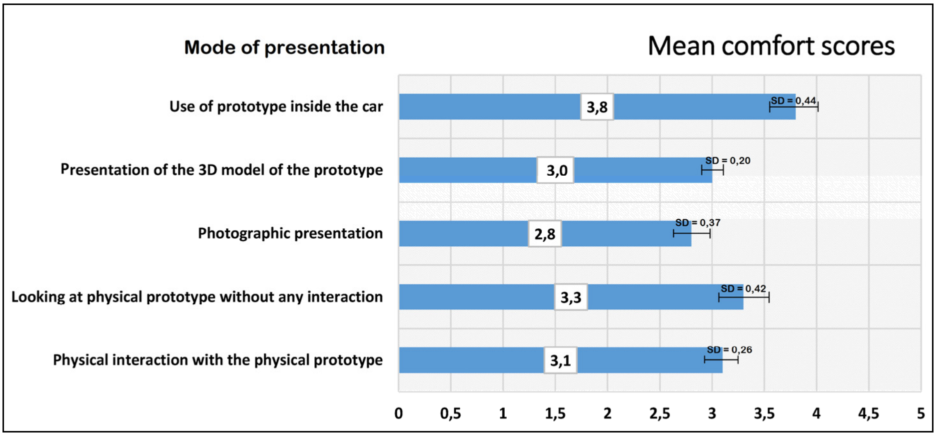

Fig. 5.10: Average comfort score related to the different kinds of presentation of the seat

The results of the questionnaire for each type of presentation were compared with results obtained by the physical interaction with the automobile seat inside the car. The scores, in most cases, were highest when the subjects were inside the car (see Figures 5.11–5.14). A high value of comfort rating inside the car was expected because the specific car (Ford Fiesta MY 2005) and a FCA car (Fiat Punto MY2009), were previously tested for comfort assessment [43]. The analysis of variance confirms that the data-dispersion is limited and the subjects' evaluation are really different when the mode of presentation/interaction changes.

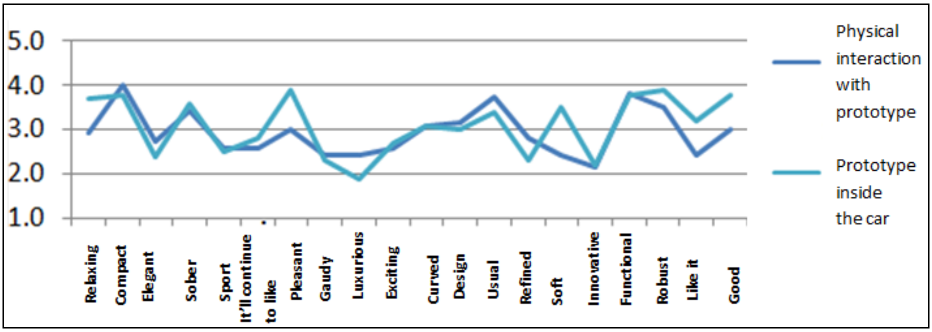

Fig. 5.11: Comparison of the questionnaire average scores between the physical interaction with the prototype and interaction with the seat inside the car

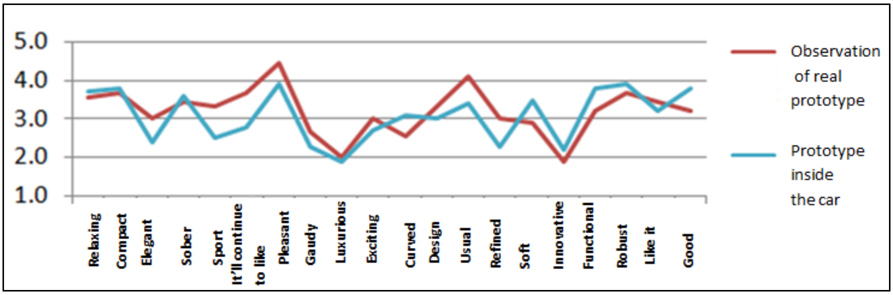

Fig. 5.12: Comparison of the questionnaire scores between observation of real prototype and interaction with the seat inside the car

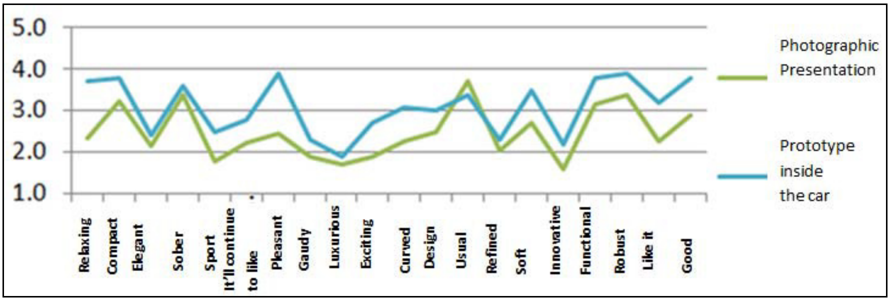

Fig. 5.13: Comparison of the questionnaire scores between the photographic presentation of the seat and interaction with the seat inside the automobile

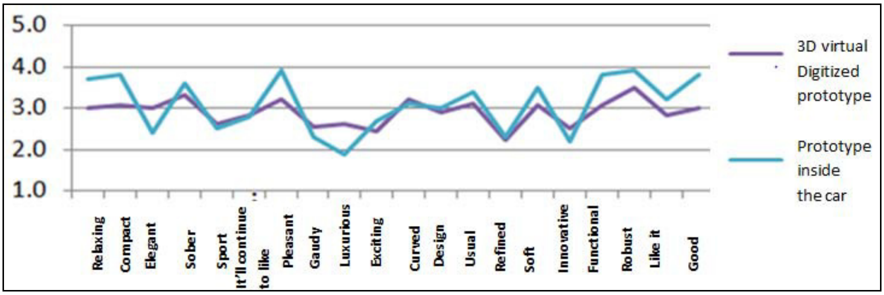

Fig. 5.14: Comparison of the questionnaire scores between the 3D virtual digitized prototype and interaction with the seat inside the automobile

5.6 Conclusions

The aim of this study was to demonstrate that the feeling of comfort/discomfort related to an object cannot be determined if only the object itself is considered. The study has tested the hypothesis of the NC-model: According to the NC-model, to evaluate levels of satisfaction of a condition of service, all the elements of environment and how they interact with the object itself have to be considered. To demonstrate this hypothesis, the authors applied the matrix to the case of the automobile seat. The automobile seat was evaluated by a sample of subjects in different ways, adding some information each time: from a simple photo to finally inside the automobile. From the analysis of the questionnaire results, the seat when evaluated inside the car scored as most comfortable. In this case, in fact, the comfort index is 3.8, higher than all other ways of representation.

This demonstrates that it is insufficient to evaluate only the finishes of the surfaces, the softness and the compactness of the coatings (construction interaction), only the colours and the geometry (observation of real prototype without interaction and photographic interaction) or only the 3D vision of the object. Instead, it is necessary to evaluate the object inside its natural environment and during a simulation of the activity. In this way, all the elements of the matrix are considered. Therefore, it was not unexpected that the lowest index was correlated to the photographic presentation in which interaction between the user and the object is next to nothing.

The results deeply sustain the Kansei technique and prove the formulated hypothesis: to analyse an emotional design, it is necessary to apply a methodology in which all the consumers' senses are involved.

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Chapter 6

The effect of human-mattress interface's temperature on perceived thermal comfort

6 The effect of human-mattress interface's temperature on perceived thermal comfort

6.1 Summary

In recent years, methods that allow for a more objectified evaluation of perceived comfort, in terms of postural, physiological, cognitive and environmental comfort, have received a great deal of attention from researchers. This work focuses on one of the factors that influences physiological comfort perception: the temperature difference between users and the objects with which they interact. The first aim is to create a measuring system that does not affect the perceived comfort during the temperatures' acquisition.

The main aim is to evaluate how the temperature at the human-mattress interface can affect the level of perceived comfort. A foam mattress has been used for testing in order to take into account the entire back part of the human body. The temperature at the interface was registered by fourteen 100 Ohm Platinum RTDs (Resistance Temperature Detectors) placed on the mattress under the trunk, the shoulders, the buttocks, the legs, the thighs, the arms and the forearms of the test subject. 29 subjects participated in a comfort test in a humidity controlled environment.

The test protocol involved: dress-code, anthropometric-based positioning on mattress, environment temperature measuring and an acclimatization time before the test. At the end of each test, each of the test subject's thermal sensations and the level of comfort perception were evaluated using the ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) scale [1].

The data analyses concerned, in the first instance, Pearson correlations between the temperature at the interface and comfort levels of the different parts of the body. Then the same analyses were performed independently of the body parts being considered. The results demonstrated that there was no strong correlation among the studied variables and that the total increase of temperature at interface is associated with a reduction in comfort.

6.2 Introduction and the state of the art

Currently, the term comfort is often seen related to the marketing of products like chairs, cars, clothing, hand tools and even airplane tickets [2]. In the scientific literature, the term discomfort shows up often, since it is used in research. Vink & Hallbeck, in 2012 [2] studied 104,794 papers in which the term discomfort is used. Most of these studies refer to temperature as the source of the discomfort or patient comfort.

There are also many application studies that measure discomfort as a subjective phenomenon to be related to musculoskeletal injuries. The assumption is that there is a relationship between self-reported discomfort and musculoskeletal injuries. This relationship was made clearer by Hamberg-van Reenen et al. [3], where local experienced musculoskeletal discomfort was measured in different body regions on a 10-point scale six times during a working day. They longitudinally tracked over 1,700 participants and showed that those reporting higher discomfort had an increased chance of back, neck and shoulder complaints three years later (the RR varied from 1.8 to 2.6).

However, the theories relating comfort to products and product design characteristics are rather underdeveloped according to Vink & Hallbeck [2], to Naddeo et al. [4] and a new model (Fig. 6.1) was proposed by Vink [5]. The Artefact (A) and Human (H) are in an environment. Usage (U) causes an Interaction (I) between the human and the artefact, which causes human body effects (B). Then it will be Perceived (P) in the human brain, which is influenced by Expectations (E) and could give a certain Comfort (C) and Discomfort (D).

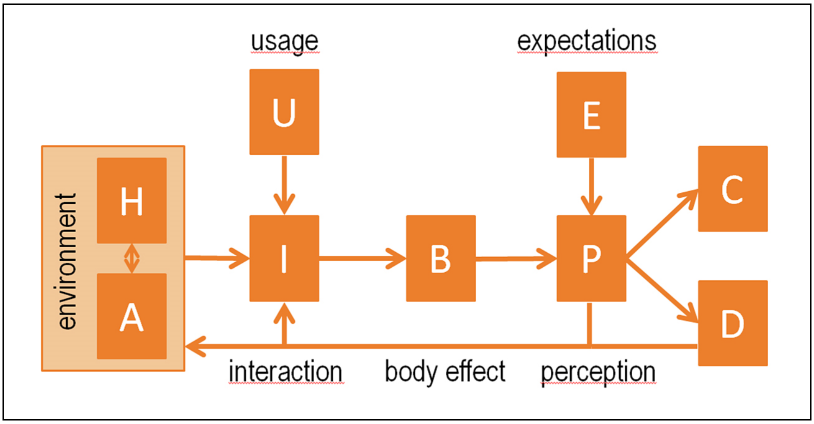

Fig. 6.1: Vink's comfort model. The Artefact (A) and Human (H) are in an environment. Usage (U) causes an Interaction (I) between the person and product, which causes human Body effects (B). Then it will be Perceived (P) in the human brain, which is influenced by Expectations (E) and could give a certain Comfort (C) and Discomfort (D)

As described by Vink [6] the interaction in this model can be recorded by many sensors. There is locally visual input, smell and sound and all over the body input from temperature, propriocepsis and pressure and touch. These all influence comfort and discomfort. Interestingly, Chen et al. [7] described the same sensory input related to sleep quality. They state that sensory input plays an important role in neuronal activities during sleep. The temperature, light, sound and smell around the environment influences the individual's sleep pattern and related functions. The pressure distribution on the human body during sleep is another aspect of sensory input that plays a role. Some aspects about influence of posture (Verhaert et al. [8]; Park et al. [9]; Naddeo et al. [10]) and biomechanics of the spine (De Vocht et al. [11]; Jacobson et al. [12]; Verhaert et al. [13]) on perceived comfort/discomfort have been already studied but have been never deepened through a statistical approach. Expectation also plays a fundamental role in the comfort perception as described in Naddeo et al. [14]. "Over-concentrated" or "over-even" pressure distribution may influence the sensory input and disturb sleep-related brain networks or may change the physiological posture for better sleep. In fact, sleep is a complex phenomenon: sleep quality is affected by a combined action of physiological, psychological and external environments (Chen et al. [15]). Lee and Park [16] studied the influence of mattress types on sleep quality and skin temperature. They found that when subjects slept on a self-reported “comfortable” mattress, the sleep efficiency and the skin’s temperature were higher than when subjects slept on an “uncomfortable” mattress. This relationship between temperature and comfort during sleeping is interesting for studies on comfort in general as temperature is most often mentioned in the scientific literature and might be relevant. The research questions are: how and how much the perceived temperature can affect the perceived comfort? What are, if any, the most sensible human body parts to the temperature changes? Are these changes detectable and can be measured in a controlled environment. To answer to this question some hypotheses have been formulated:

1. The mattress is comfortable under the postural point of view (as detected in a previous research-work[7] not published for “non-disclosure agreement” reason);
2. A temperature growth will be found in all tests, because the body temperature is higher than the mattress’ one;
3. The increase of temperature might cause a decrease of perceived comfort but not a discomfort state for the subjects;
4. Different body parts could detect the temperature increase in a different way.
5. Thermal comfort is defined by ASHRAE Standard 55 (American Society of Heating, Refrigerating and Air-Conditioning Engineers) (ASHRAE, 2003 [1]) as a mental condition expressing the satisfaction of the individual for the thermal environment in which he or she operates.

6.3 Material and methods

6.3.1 Purpose

One of the factors that could contribute to comfort/discomfort perception is the thermal equilibrium caused by the interaction between a person and the object with which he interacts (Naddeo et al. [4]; Vink [5]). This assumption is easy to demonstrate, especially in the cases when nearly the whole body is in contact with an object, even for a long period of time, such as the interaction between a person and a seat or a mattress. Yao et al. [17] studied the relationship between skin temperature and

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[7] *The research work was funded to University of Salerno by a private company and is under UE patenting.*

thermal comfort, checking the best method to analyse the phenomenon and the correlation between comfort perception and skin temperature.

The purpose of the study was to evaluate how the temperature at the human-mattress interface can affect the level of perceived comfort and how the data acquisition can be made without affecting the subjects' perceived comfort. To do that, several tests involving the entire back part of a human body were performed with the subject lying, in supine position, on a mattress.

6.3.2 Participants

Participants were recruited from young professors and students in their last year of Master's degree courses in Mechanical and Management Engineering at the University of Salerno.

The sample can be considered homogenous: 29 subjects (12 women and 17 men) whose age was between 23 and 40 years. Most of participants came from the same geographical area and were accustomed to similar weather conditions, so their sensibilities to cold/warm were likely to be similar as well. The sample was clustered in terms of age, gender, anthropometric characteristics (height, weight and anthropometric percentile). Subjects were asked to use standardized clothes (no shoes, long sleeves' shirt and shorts or thin cotton trousers). All subjects who participated gave their informed written consent. No subjects reported any musculoskeletal or neurological conditions that precluded their participation in the study.

6.3.3 Testing devices

A mattress, a temperature data acquisition system, and a questionnaire were used in this study.

The mattress used was the "SHIRLEY" model of the Valflex® line. This is an anatomical multi-foam mattress in which three different layers are combined one on top of the other: the top layer is made of Multi Foam Fresh Gel, the middle layer is made of Mind Foam Memory Effect with massaging effect and the lower layer is made of Technocell AquPur high-density with open cell, which ensures very good weight support. The total mattress' height was 22 cm, 80 cm wide by 188 cm in length. The mattress was covered with an elastic cover made of cotton and polyamide that hid the internal characteristics of the mattress and helped to distribute the weight of subjects in a proper manner.

The temperature measurement system consisted of fourteen 100 Ohm Platinum RTDs (resistance temperature detectors), four RTD analog inputs, each with four channels (Type 9217, National Instruments Italy S.r.l). The accuracy of measurement of the RTDs used was ±0.05°C.

The RTDs were placed on the mattress and covered by a thin elastic cover made of cotton that did not compromise the validity of the tests and, by limiting direct interaction between the subject and the sensors, prevented the subjects from being annoyed by the RTDs when they were lying down. The RTDs were placed on the left and right sides of the mattress under the trunk (2), the shoulders (2), the buttocks (2), the legs (2), the thighs (2), the arms (2) and the forearms (2), as shown in Fig. 6.2.

Fig. 6.2: Location of RTDs on the mattress pad material (on the left, under the thin cover) and their corresponding position on the subject's skin (red points)

Because the anthropometrics measurements of the subject were not identical, the subjects were clustered in four groups by height and, for each group, the RDTs were relocated.

Based on the "Thermal comfort" definition by ASHRAE *Standard 55* [1], subjects were asked directly about thermal sensations and their "votes" were expressed by a numerical value on the ASHRAE scale. The questionnaire used is shown in Fig. 6.3.

	Evaluation Index						
	Very hot with excessive discomfort	Hot with strongly localized discomfort	Slightly hot with slight discomfort	Neither hot nor cold. Comfort	Slightly cool with slight discomfort	Fresh with strongly localized discomfort	Cold with excessive discomfort
Shoulder (Right Side)							
Shoulder (Left Side)							
Right Arm							
Left Arm							
Right Forearm							
Left Forearm							
Trunk (Right Side)							
Trunk (Left Side)							
Buttock (Right Side)							
Buttock (Left Side)							
Right Thigh							
Left Thigh							
Right Leg							
Left Leg							

Fig. 6.3: Comfort questionnaire (Body parts in the rows, evaluation value in the columns)

6.3.4 Procedures

Testing was conducted in a humidity-controlled room (50% ± 2%). Three testing sessions were conducted on different days. The ambient temperature was registered but not controlled. Different ambient temperatures were desirable because one of the aims of this study was to compare the comfort index and the ambient temperature. A rest period of 30 min (participants were seated during this period) was provided before the test sessions to acclimatize the subjects to the environmental conditions (Hedge et al. [18]; Bartels [19]). After this period, the participants were asked to lie down on the mattress, making sure that each part of the body was on the correct RDT. The duration of the test was 15 minutes for all participants. This time duration was chosen on the basis of the experience of Karimi et al. [20]. They reported a threshold time of 10 min for a participant to achieve thermal neutrality at all contact points on a seat pan, without any external heating or cooling. A one-hour test, made with two subjects, shows that, in static conditions, a good thermal equilibrium is reached after about 12 min.

Additionally, the experience of mattress producers and sellers suggested that, both in the case of testing a new mattress before buying and in the case of using a mattress before going to sleep, the time of lying on the mattress is often less than 15 minutes and this was taken into consideration when determining the duration of the test. In fact, a normal subject generally needs less than 15 minutes, in a steady posture, to begin to sleep. During sleep, perceptions of thermal comfort cannot be evaluated.

Temperature data at the interfaces was recorded every 6 seconds for the duration of the session starting from the time just before the participants lay down on the mattress.

After 14 minutes, while the subject was still lying on the mattress, questions about perceived comfort were asked. At the end of the test, the subjects were asked if they had detected something under their skin, in order to understand the “detectability” of the acquisition system.

6.3.5 Data processing

For each part of the body, a multivariate analysis was performed to determine possible correlations among the variables. The statistical analysis software SPSS rel.13 was used to perform these analyses. Pearson correlation coefficients were calculated to determine the strength of the relationships between all the variables. Data clustering on temperatures was made in order to better understand the significance of correlations and the analysis of the values of variances was used for highlighting possible trends.

6.3.6 Collected data

For each test, three kinds of data were collected: anthropometric, temperature and thermal sensations.

A summary of the anthropometric data is provided in Table 6.1.

	Age (years)	Stature (cm)	Mass (Kg)	Body surface Area (m^2)	Body Fat (%)	Body Mass Index
Mean	26.10	173.93	68.83	1.82	19.95	22.64
Std. Deviation	3.57	7.82	10.67	0.17	4.21	2.25
Minimum	23	159	51	1.51	14.24	18.87
Maximum	40	190	90	2.12	29.88	28.41

Table 6.1: Descriptive statistics of selected variables for the participant population

During the 15 minutes of the test, 150 temperatures were registered for each part of the body (left and right).

Data acquired are shown below:

(1) Ti (°C): the first registered temperature at the interface

(2) Tf (°C): the last registered temperature at the interface

(3) Tm (°C): the average temperature at the interface during the 15-minutes test period

(4) Ta (°C): the average ambient temperature during the 15-minutes test period

(5) ΔT1 (°C): the difference between the average temperature and the average ambient temperature

(6) ΔT2 (°C): the difference between the initial temperature and the final temperature at the interface

(7) ΔT3 (°C): the difference between the final temperature at the interface and the average ambient temperature

(8) Hr (°C/min): the heating rate, obtained by dividing ΔT2 by 15 (minutes)

The choice of these parameters has been based on the thermal behaviour of a complex system (human body – mattress) in a closed environment: all the parameters that can affect the thermal behaviour, and consequently the perceived thermal comfort, have been monitored and recorded. At the end of the test, the tester asked each subject to rate the perceived thermal comfort for each part of her/his body.

Because of the symmetry of the human body, averages of data (Index of Comfort = I.C.) for left (I.C. SX) and right (I.C. DX) for each body part were made in order to get total data for each body part. The values used by the questionnaire to record thermal sensations (and the related I.C.) are shown in Table 6.2.

Very hot with excessive discomfort	0
Hot with strongly localized discomfort	1
Slightly hot with slight discomfort	2
Neither hot nor cold. Comfort	3
Slightly cool with slight discomfort	2
Fresh with strongly localized discomfort	1
Cold with excessive discomfort	0

Table 6.2: Index of Comfort (I.C.) associated with each item of the questionnaire

An example of the collected data are shown in Table 6.3.

	SHOULDER									
№	I.C. DX	I.C. SX	I.C.	Ti	Tf	Hr	ΔT1	ΔT2	Ta	ΔT3
1	1	1	1	32,64	32,88	1,61	7,06	0,24	25,69	7,19
2	2	2	2	36,98	37,17	1,21	10,81	0,18	26,27	10,90
3	2	2	2	35,42	35,62	1,30	9,28	0,20	26,24	9,38
4	3	3	3	34,41	34,54	0,92	8,64	0,14	25,83	8,71
5	2	2	2	36,47	36,60	0,86	10,21	0,13	26,33	10,27
6	2	2	2	35,86	36,04	1,25	9,62	0,19	26,34	9,70
7	2	1	1,5	33,82	33,87	0,36	7,41	0,05	26,44	7,43
8	2	2	2	35,75	35,87	0,78	10,48	0,12	25,49	10,38
9	3	3	3	37,02	37,15	0,91	11,01	0,14	26,08	11,07
10	3	3	3	36,01	36,15	0,92	10,04	0,14	26,04	10,11
11	3	2	2,5	35,32	35,52	1,36	9,42	0,20	26,00	9,52
12	3	3	3	33,94	34,02	0,53	7,68	0,08	26,30	7,72
13	2	2	2	36,41	36,56	0,98	11,54	0,15	24,95	11,61
14	3	3	3	36,81	36,91	0,71	12,54	0,11	24,32	12,59
15	2	2	2	36,22	36,40	1,22	12,19	0,18	24,13	12,27
16	3	3	3	35,95	36,12	1,15	11,90	0,17	24,14	11,98
17	1	2	1,5	35,61	35,82	1,39	12,08	0,21	23,64	12,18
18	3	2	2,5	35,75	35,91	1,05	11,81	0,16	24,03	11,89
19	2	2	2	36,24	36,36	0,81	11,95	0,12	24,36	12,00
20	3	3	3	35,94	36,06	0,84	6,78	0,13	29,22	6,84
21	3	3	3	35,80	36,00	1,35	7,22	0,20	28,68	7,32
22	1	1	1	35,17	35,41	1,63	7,03	0,24	28,27	7,15
23	3	3	3	34,98	35,23	1,70	8,83	0,25	26,27	8,96
24	3	3	3	35,87	36,04	1,17	9,24	0,17	26,71	9,33
25	3	3	3	36,32	36,52	1,33	9,11	0,20	27,31	9,21
26	2	2	2	36,66	36,78	0,80	7,56	0,12	29,16	7,62
27	2	2	2	36,72	36,83	0,73	7,41	0,11	29,36	7,47
28	2	2	2	36,51	36,63	0,80	6,94	0,12	29,63	7,00
29	2	2	2	37,16	37,27	0,73	9,28	0,11	27,94	9,33

Table 6.3: Summary of data collected during the test for the shoulders (numbered subjects in the rows)

A summary of the variables recorded for each part of the body are provided in the Tables 6.4, 6.5, 6.6, 6.7, 6.8, 6.9, 6.10.

SHOULDER	Minimum	Maximum	Mean	Std. Deviation
I.C. DX	1,00	3,00	2,34	0,67
I.C. SX	1,00	3,00	2,28	0,65
I.C.	1,00	3,00	2,31	0,63
Ti	32,64	37,16	35,78	1,04
Tf	32,88	37,27	35,94	1,03
Hr	0,36	1,70	1,05	0,33
ΔT1	6,78	12,54	9,49	1,88
ΔT2	0,05	0,25	0,16	0,05
Ta	23,64	29,63	26,39	1,72
ΔT3	6,84	12,59	9,56	1,87

Table 6.4: Descriptive statistics for the shoulders

ARM	Minimum	Maximum	Mean	Std. Deviation
I.C. DX	1,00	3,00	2,28	0,70
I.C. SX	1,00	3,00	2,21	0,68
I.C.	1,00	3,00	2,24	0,64
Ti	32,64	37,02	35,49	1,02
Tf	32,88	37,17	35,66	1,02
Hr	0,81	2,30	1,31	0,36
ΔT1	3,57	10,66	7,24	1,71
ΔT2	0,12	0,34	0,20	0,05
Ta	23,64	29,63	26,39	1,72
ΔT3	3,64	10,79	7,33	1,71

Table 6.5: Descriptive statistics for the arms

FOREARM	Minimum	Maximum	Mean	Std. Deviation
I.C. DX	1,00	3,00	2,17	0,76
I.C. SX	0,00	3,00	2,14	0,79
I.C.	0,50	3,00	2,16	0,75
Ti	29,39	35,95	33,14	1,58
Tf	29,51	36,08	33,22	1,63
Hr	0,10	2,87	0,81	0,54
ΔT1	3,89	9,75	6,80	1,69
ΔT2	0,02	0,43	0,12	0,08
Ta	23,64	29,22	26,15	1,40
ΔT3	3,88	9,81	7,24	1,49

Table 6.6: Descriptive statistics for the forearms

TRUNK	Minimum	Maximum	Mean	Std. Deviation
I.C. DX	1,00	3,00	1,79	0,73
I.C. SX	1,00	3,00	1,79	0,73
I.C.	1,00	3,00	1,79	0,69
Ti	32,34	36,60	34,83	0,99
Tf	32,49	36,72	35,02	0,98
Hr	0,75	2,03	1,24	0,35
ΔT1	4,56	12,34	8,55	1,96
ΔT2	0,11	0,31	0,19	0,05
Ta	23,64	29,22	26,15	1,40
ΔT3	5,24	12,39	9,04	1,59

Table 6.7: Descriptive statistics for the trunk

BUTTOCK	Minimum	Maximum	Mean	Std. Deviation
I.C. DX	0,00	3,00	1,62	0,78
I.C. SX	0,00	3,00	1,55	0,78
I.C.	0,00	3,00	1,59	0,77
Ti	30,62	36,07	34,15	1,28
Tf	30,86	36,22	34,39	1,25
Hr	1,03	2,75	1,58	0,42
ΔT1	5,47	11,83	8,01	1,71
ΔT2	0,15	0,41	0,24	0,06
Ta	23,64	29,22	26,27	1,54
ΔT3	5,57	11,90	8,12	1,70

Table 6.8: Descriptive statistics for the buttocks

THIGH	Minimum	Maximum	Mean	Std. Deviation
I.C. DX	0,00	3,00	1,72	0,75
I.C. SX	0,00	3,00	1,69	0,76
I.C.	0,00	3,00	1,71	0,74
Ti	31,03	35,82	34,38	1,20
Tf	31,28	35,97	34,58	1,18
Hr	0,62	2,60	1,36	0,51
ΔT1	5,46	11,42	8,10	1,61
ΔT2	0,09	0,39	0,20	0,08
Ta	23,64	29,22	26,15	1,40
ΔT3	5,59	11,49	8,60	1,46

Table 6.9: Descriptive statistics for the thighs

LEG	Minimum	Maximum	Mean	Std. Deviation
I.C. DX	1,00	3,00	1,59	0,63
I.C. SX	1,00	3,00	1,62	0,62
I.C.	1,00	3,00	1,60	0,59
Ti	31,00	36,40	34,54	1,35
Tf	31,09	36,55	34,72	1,37
Hr	0,23	2,33	1,22	0,47
ΔT1	4,71	11,45	8,25	1,94
ΔT2	0,03	0,35	0,18	0,07
Ta	23,64	29,22	26,15	1,40
ΔT3	4,75	11,56	8,74	1,72

Table 6.10: Descriptive statistics for the legs

Data was gathered to evaluate the impact of individual characteristics of the subjects (i.e. age, gender, Body Mass Index, body fat and body surface area) and the impact of thermal parameters (Ti, Tf, Tm, Ta, ΔT1, ΔT2, ΔT3, Hr) on thermal sensations, as well as on comfort perception. There are previous studies that correlate individual characteristics with thermal sensation (Tuomaala et al. [21]), but no works have been found in the literature that discuss the correlation between temperature at the human-mattress interface and thermal sensation. For each part of the body, a multivariate analysis was performed to determine possible correlations among the variables. The statistical analysis software SPSS rel.13 was used to perform these analyses. Pearson correlation coefficients were calculated to determine the strength of the relationships between all the variables, as shown in Table 6.11.

Correlations			Percentile	Tm	Ti	Tf	Hr	ΔT1	ΔT2	ΔT3
SHOULDER	IC	Pearson Correlation	0,304	0,212	0,217	0,212	-0,139	0,133	-0,139	0,133
		Sig. (2-tailed)	0,109	0,269	0,258	0,269	0,471	0,492	0,473	0,493
ARM	IC	Pearson Correlation	.387(*)	-0,113	-0,114	-0,109	0,141	0,084	0,141	0,087
		Sig. (2-tailed)	0,038	0,561	0,555	0,572	0,466	0,665	0,464	0,655
FOREARM	IC	Pearson Correlation	-0,02	-.411(*)	-.409(*)	-.410(*)	-0,189	-0,115	-0,189	-0,273
		Sig. (2-tailed)	0,92	0,027	0,028	0,027	0,327	0,552	0,327	0,152
TRUNK	IC	Pearson Correlation	0,248	-0,124	-0,129	-0,119	0,211	0,154	0,21	0,185
		Sig. (2-tailed)	0,195	0,523	0,504	0,538	0,273	0,424	0,274	0,335
BUTTOCK	IC	Pearson Correlation	-0,028	0,043	0,038	0,031	-0,147	0,232	-0,147	0,23
		Sig. (2-tailed)	0,886	0,824	0,844	0,873	0,447	0,225	0,448	0,23
THIGH	IC	Pearson Correlation	0,18	-0,258	-0,196	-0,181	0,283	0,259	0,284	0,183
		Sig. (2-tailed)	0,351	0,177	0,308	0,348	0,137	0,175	0,135	0,341
LEG	IC	Pearson Correlation	-0,169	-0,098	-0,102	-0,091	0,197	0,12	0,198	0,135
		Sig. (2-tailed)	0,382	0,612	0,599	0,64	0,305	0,535	0,304	0,484

**Correlation is significant at the 0.01 level (2-Tailed).
* Correlation is significant at the 0.05 level (2-tailed).

Table 6.11: Statistical correlations among the variables

All the subjects, at the end of the test, have answered "No" to the question about detectability of acquisition system.

6.4 Result and discussion

For each part of the body, statistical analyses were made to verify if there were correlations between the comfort index and the other variables (gender, stature, age, weight, anthropometric percentile, body surface area, body fat, Body Mass Index, Ti, Tf, Tm, Ta, ΔT1, ΔT2, ΔT3, Hr). The Pearson index did not reveal high correlations among the variables. In particular, the Pearson index revealed a correlation between percentile and IC index (the positive correlation is significant at the 0.05 level) in the case of the arms, and negative correlations between IC index and Tm, Ti and Tf in the case of the forearms (the negative correlations are significant at the 0.05 level).

While in the first part of the study, the analysis was related to the different parts of the body, the later analysis was aimed at determining the possible correlations between the registered temperature data on the skin at the interface and perceived comfort, independent of the body parts for which data was gathered. In particular, the correlations between IC index and ΔT2, ΔT3 and Tf were evaluated. For each pair of variables analysed, 203 data (7 body parts * 29 subjects) were considered. An example is shown in Appendix 1.

For each variable (ΔT2, ΔT3 and Tf) considered, total data were divided into 4 equal sub-ranges and the related comfort data were clustered according to these sub-ranges. For each sub-range, the average and the variance of the comfort indices were calculated. Tables 6.12, 6.13 and 6.14 show the processed data related to ΔT2, ΔT3 and Tf.

ΔT2 (°C)	IC_mean	VAR
0.015-0.12	1,952	0,477
0.121-0.220	1,926	0,559
0.221-0.330	1,924	0,547
0.331-0.430	1,857	0,714

Table 6.12: Processed data related to ΔT2 (in the first column: the ΔT2 intervals)

ΔT3 (°C)	IC_mean	VAR
3.640-5.880	2,079	0,674
5.881-8.120	1,819	0,608
8.121-10.350	1,907	0,501
10.351-12.590	2,286	0,370

Table 6.13: Processed data related to ΔT3 (in the first column: the ΔT3 intervals)

Tf (°C)	IC_mean	VAR
29.475-31.420	2,368	0,496
31.421-33.370	1,842	0,724
33.371-35.320	1,861	0,516
35.321-37.265	1,915	0,504

Table 6.14: Processed data related to Tf (in the first column: the ΔT2 intervals)

The study demonstrated that there was a trend, although not one that is very evident, between the Mean Comfort Index and increases of temperature (Fig. 6.4). With increases of ΔT2, the level of perceived discomfort decreases. However, the analysis of the values of variances did not confirm this trend (Table 6.13), but confirmed, instead, the results of the statistical analysis reported in Appendix of [22].

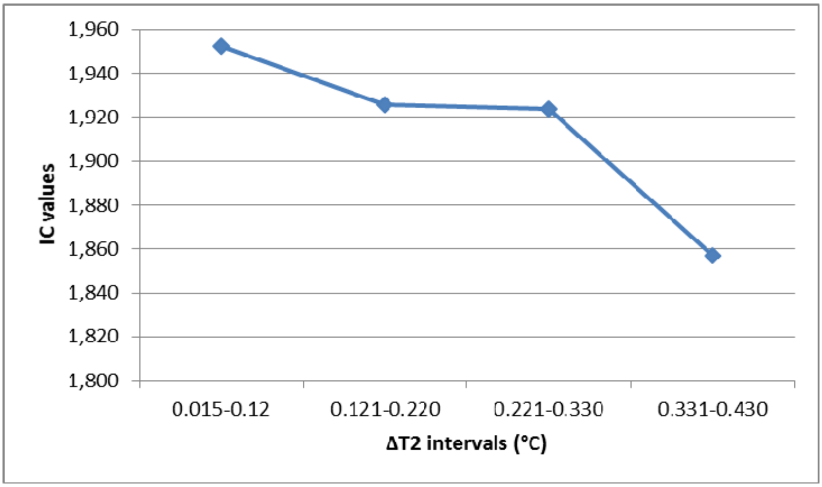

Fig. 6.4: Graph of the trend of the IC related to the ΔT2

An analysis similar to that presented for the ΔT2 and final temperature was also made for the ΔT3. The graphs presented in Fig. 6.5 and Fig. 6.6 demonstrate that there were no further correlations among the variables.

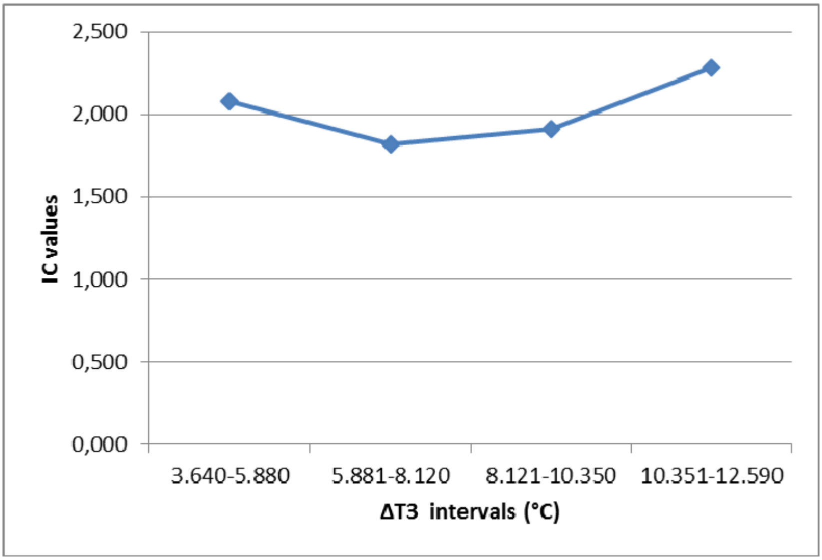

Fig. 6.5: Graph of the trend of the IC related to the ΔT3

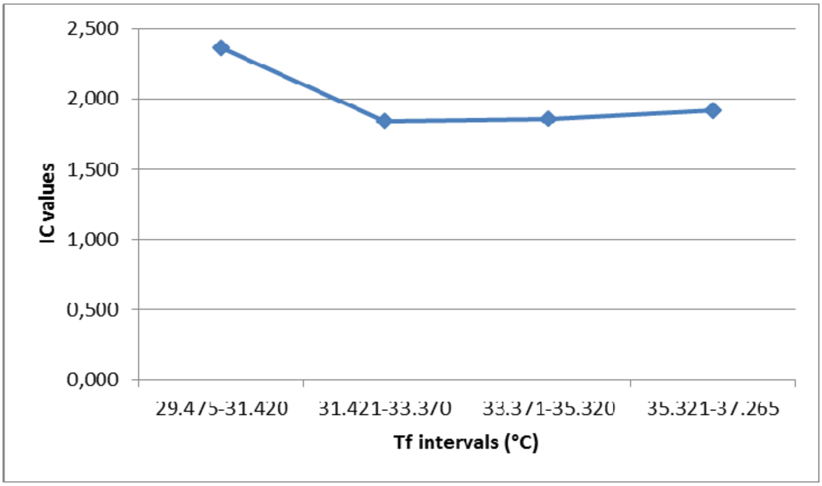

Fig. 6.6: Graph of the trend of the IC related to the Tf

6.5 Conclusion

A psychophysical approach has been used to evaluate if there is a relationship between the temperature of the skin at the interface between the human body and the level of perceived comfort. To assess the level of comfort perceived by the user in relation to the temperature at the interface, it was decided to perform the test on a mattress to be able to consider the interactions of whole body with the mattress.

The way to do that was the creation of a measuring system that did not affect the perceived comfort during the temperatures' acquisition. The use of flat and thin RTDs under a soft elastic cover has permitted to obtain a "not-detectable by users" acquisition system.

During the tests, two types of data were recorded: the temperature at the interface and the subjective comfort perceptions of the participants.

In the first part of the study, the correlations between the temperature at the interface and comfort perception were evaluated in relation to each part of the body (arms, forearms, trunk, buttocks, legs and thighs). The Pearson index did not reveal high correlations among the considered variables. In particular, the Pearson index revealed negative correlations between IC index and Tm, Ti and Tf in the case of the forearms.

In the second part of the study, the aim was to verify the correlations between the Comfort Index and the skin temperature at the interface independently of the body parts considered. In particular, the correlations between IC index and ΔT2, ΔT3 and Tf were evaluated.

The analyses of the data confirmed the lack of strong correlations. The only relevant result regarded the correlation between increases of temperature, ΔT2, and the Comfort Index. The study demonstrated that a correlation exists between these two variables. Increases of the ΔT2 (total increase of temperature at interface) were associated with a reduction in comfort. This result is reflected in the fact that humans register for a certain amount of heat centrally in the brain, while the cold is mainly recorded from peripheral sensors. This study suggest to designers that, when designing a new product for "bed" companies, the problem of interface temperature might have a minor priority towards other issues that are related, for example, with the acquired posture and the map of pressures; this is true since the temperature is always lower than the "normal" skin temperature (about 37°C). For higher temperature, the effect may drastically change. Limitations of this study can be found in the experimental setup, in which the ambient temperature cannot be controlled (even if no correlation between perceived comfort and ambient temperature has been found), and in the lack of information about perspiration/sweat of subjects' skin during the test; both these aspect can affect the perceived comfort and might be controlled/acquired in future experiments. Future developments can be thought about understanding the correlation between temperature and pressure at interface, not only in supine position but also in prone and lateral position. Another limitation of the study is about the limited range (about 23-30°C) of temperatures recorded in the climate chamber. In extreme situations, the results of the same experiment could be different.

6.6 Acknowledgement

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Chapter 7

The effect of posture, pressure and load distribution on perceived (dis)comfort. Analysis of a school chair with rigid seat and without armrests

7 The effect of posture, pressure and load distribution on perceived (dis)comfort. Analysis of a school chair with rigid seat and without armrests

7.1 Summary

The study of ergonomics and workplace comfort/discomfort has been a major topic of interest to scientific literature since the introduction of ISO 11228. Several health and safety guidelines have been accepted and developed as a result. Over the past 30 years, researchers have attempted to understand the mechanisms underlying perceptions of (dis)comfort for a seated subject. Of all the comfort-related topics, this is perhaps the most challenging. Three main factors are recognized in the literature as paramount for the comfort performance of a seat: human body posture, pressure at interface, and load distribution on the contact area.

This study investigates the relationships between these three factors and examines their significance for (dis)comfort perception. Physiological factors (e.g. blood vessels constraint, sweat and muscular fatigue) are known to play a role in (dis)comfort perception, and have been considered as a consequence of the three main parameters above. An explanation is given for this hypothesis.

To simplify the analysis and prevent other factors (e.g. a soft seat pan or the asymmetric configuration of the load) from affecting overall perception or otherwise modifying the results, experimental tests were conducted using a school chair with a rigid seat pan and no armrests.

Our conclusions show the levels of correlation between acquired information and perceived (dis)comfort. These results have been compared with others from the literature obtained under similar conditions.

7.2 Introduction and state of the art

Overall comfort can be defined as the measurement of the “level of well-being” perceived by humans interacting with an environment or an object. This level is challenging to detect and measure, however, as it is affected by subjective judgments and must be analysed using quantitative/qualitative methods.

In previous chapter a wide research about the state of the art regarding, (dis)comfort perception models, and about factors that affect this perception, has been still presented.

The following five main factors regarding the relationship between subjective perceptions of comfort/discomfort and products, processes, interactions, environment, and users have been underlined: sensory input (De Korte et al. [1]; Vink et al [2]); activities that occur during measurement and that have an influence on comfort (Groenesteijn et al. [3]; Ellegast et al. [4]); different bodily regions (Franz et al. [5]; Kong et al. [6]); the effect of product contours on comfort (Kamp [7]; Naddeo et al. 2009 [8], Noro et al. [9]); and physical loading (Borg [10]; Kee et al. [11], Di Pardo et al. [12]; Zenk et al. [13], Apostolico et al. [14]).

Probably, the body effects act directly on (dis)comfort perception and the interaction that causes them, as described by Vink [15], can be recorded by many “sensors”. There is local input in the form of visuals, smell and sound; and whole-body input in the form of temperature, propriocepsis, pressure and touch. All of these have an influence on perceived comfort and discomfort. Most studies investigate the effect of pressure variables, such as mean and peak pressure (Hostens et al. [16], Moes [17]), contact area (Paul et al. [18]; Kyung and Nussbaum [19]; Vos et al. [20]) and pressure distribution (Mergl [21]; Zenk [22]). Mergl [21] and Zenk [13,22], for example, defined the ideal pressure distribution for a car driver. Even though pressure distribution seems to be the best objective measure for discomfort (De Looze et al. [23]), it is influenced by other variables, such as posture (Tessendorf et al. [24]; Oyama et al. [25]; Zhiping and Jian [26]; Naddeo et al. [27]), movement (Wang et al [28]; Ciaccia and Sznelwar [29]), expectations (Naddeo et al. [30]) and first sight (Vink [31]) – none of which are taken into account in the majority of studies. Helander and Zhang [32] and de Looze et al. [23] state that discomfort is more related to physical factors, while comfort is more related to luxury and feelings of refreshment. The present study incorporates the following hypotheses (Hi), which are based on the literature and can be easily be considered as a standard, common knowledge:

- H1: the greatest pressure will be found in the buttocks area, as the weight of the torso is directly above this point (Zenk et al [13]);
- H2: the greater the body mass index (BMI) of the subject, the larger the contact area (Vink [31]);
- H3: stretched legs lead to increased pressure on the front of the thighs (Zenk et al. [13]);
- H4: comfort is higher when pressure is distributed over a larger area (Hiemstra-van Mastrigt [33]);
- H5: there is always a correlation (sometimes strong and sometimes moderate) between anthropometric measures and pressure factors (distribution, peak, average) (Hiemstra-van Mastrigt [33]).

The aim of this study is to check the validity of these hypotheses and evaluate the possible correlations between pressure, discomfort and posture – the three variables of comfort and discomfort linked to pressure distribution.

The choice of a school chair with rigid seat and without armrests is due to the very wide diffusion (as reported, for example, in the 2014 Final Report of Centre for European Policy Studies to the European Commission, DG Enterprise and Industry, within Framework Contract /ENTR/008/006EU [Renda et al. 2008]) of this kind of chairs in educational environments (like every grade schools and universities) and in public administrations, in which people have usually to stay seated for several hours.

7.3 Materials and methods

A contributing factor to the perception of discomfort is the pressure distribution caused by the interaction between a person and the object with which he/she interacts. This assumption is easy to demonstrate, especially in cases where a large proportion of the body is in contact with an object – for instance, the interaction between a person and a seat. Previous studies have demonstrated an interdependency between pressure and posture and between interface pressure and discomfort (e.g. Zenk [13]). One of the aim of this study is to further investigate the impacts of postural, personal and seat pan interface pressure upon comfort factors. Personal factors of interest include gender, weight, height and BMI. Postural factors of interest relate only to the trunk and the lower limbs (thighs and legs).

7.3.1 Subjects

Twenty-seven university students, all volunteers, participated in the experiment. None had a history of musculoskeletal diseases. The main characteristics of the subjects are summarized in Table 7.1. All subjects were informed of the nature of the tests, and written consent was obtained. The Ethical Guidelines of both the University of Salerno and Italian Law were respected while performing the tests.

	Age (years)	Weight (Kg)	Height (cm)	Body Mass Index
Mean	24.37	69.56	170.19	23.77
Std. Deviation	2.35	13.90	8.68	2.95
Minimum	21	45	154	18.3
Maximum	34	96	186	28,4

Table 7.1: Descriptive statistics of selected variables for the participant population

7.3.2 Equipment and laboratory set-up

The following equipment was used in this study for data acquisition and set-up: a simple wooden seat; a pressure data acquisition system; a photographic acquisition system; and a discomfort questionnaire. The seat and the back of this chair were rigid, with poor compliance and limited adjustability (only the height of seat pan). In this way, it was possible to evaluate the distribution of pressure and the corresponding discomfort. In the worst instance, the subject’s buttocks were completely crushed on the chair without any deformation of the seat (Fig. 7.1 (a)). To acquire the pressure distribution, a flexible Medilogic® pressure measurement mat was used. The mat was placed only on the seat, and not on the backrest. The chosen matrix was 500x500 mm2 with 480 Sensors (Fig. 7.1 (b)). The photographic acquisition system was equipped with two commercial cameras for a double-sided view (front view and upper view) (Fig. 7.2).

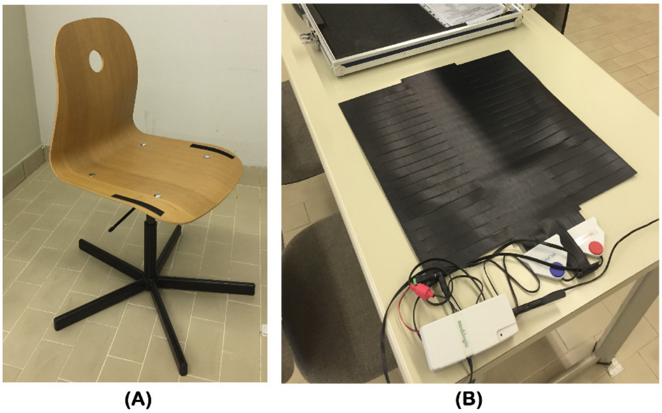
(A) (B)

Fig. 7.1: (a): Seat; (b): Pressure mat

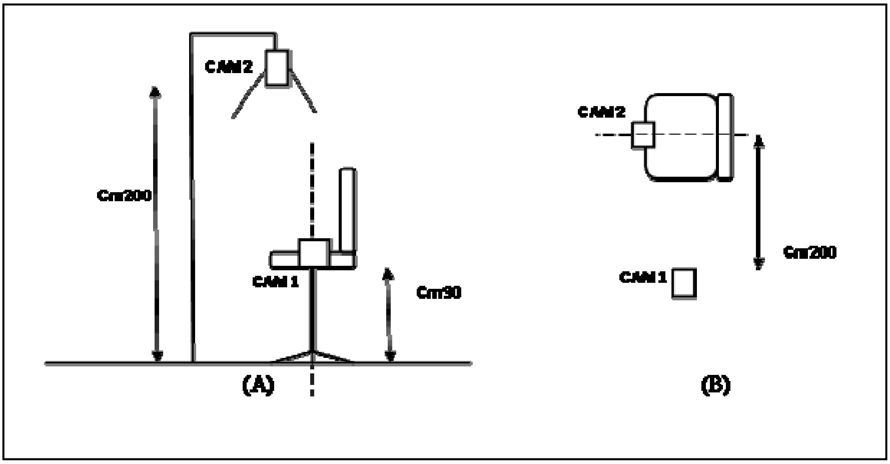

Fig. 7.2: Experimental set-up: side view (A) with the camera (cam 2) on top; upper view (B) with the camera to the side (cam 1)

The perception of discomfort was recorded using a body region discomfort questionnaire in which discomfort is evaluated using a five-point Likert scale for six specific regions of the buttocks and thighs (Fig. 7.3).

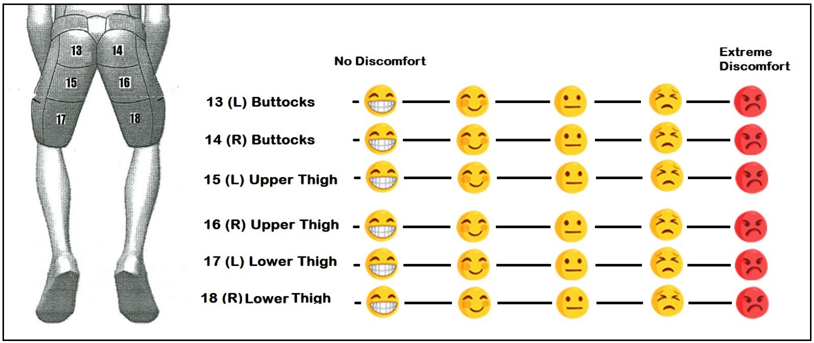

Fig. 7.3: Body region discomfort questionnaire

7.3.3 Procedure

The chosen seat, which was adjustable in height, allowed for the following nine positions to be registered (Fig. 7.4): (1A) the subject, having adjusted the seat to his/her preferred height, was asked to arrange his/her body in the most comfortable position and remain in this position for a few minutes; (1B) the subject, having adjusted the seat to the maximum height (46 cm), was asked to arrange his/her body in the most comfortable position and remain in this position for five minutes; (2B) the subject, having adjusted the seat to the maximum height, was asked to take up a position with his/her legs perpendicular to the floor; (3B) the subject, having adjusted the seat to the maximum height, was asked to position him/herself with his/her legs at maximum flexion; (4B) the subject, having adjusted the seat to the maximum height, was asked to positioned him/herself with his/her legs at maximum extension. In the cases (1C), (2C), (3C) and (4C), the subject assumed the same position as in (1B), (2B), (3B) and (4B), with the seat adjusted to the minimum height (35.5 cm), instead of the maximum. For each posture, two photos were taken – one from the left side and one from above – and the pressure was recorded. To eliminate the effects of postural comfort/discomfort while assessing the effects of pressure on overall perception, the discomfort questionnaire completed by subjects referred only to the three positions (1A, 1B and 1C) for which they chose their own most comfortable posture.

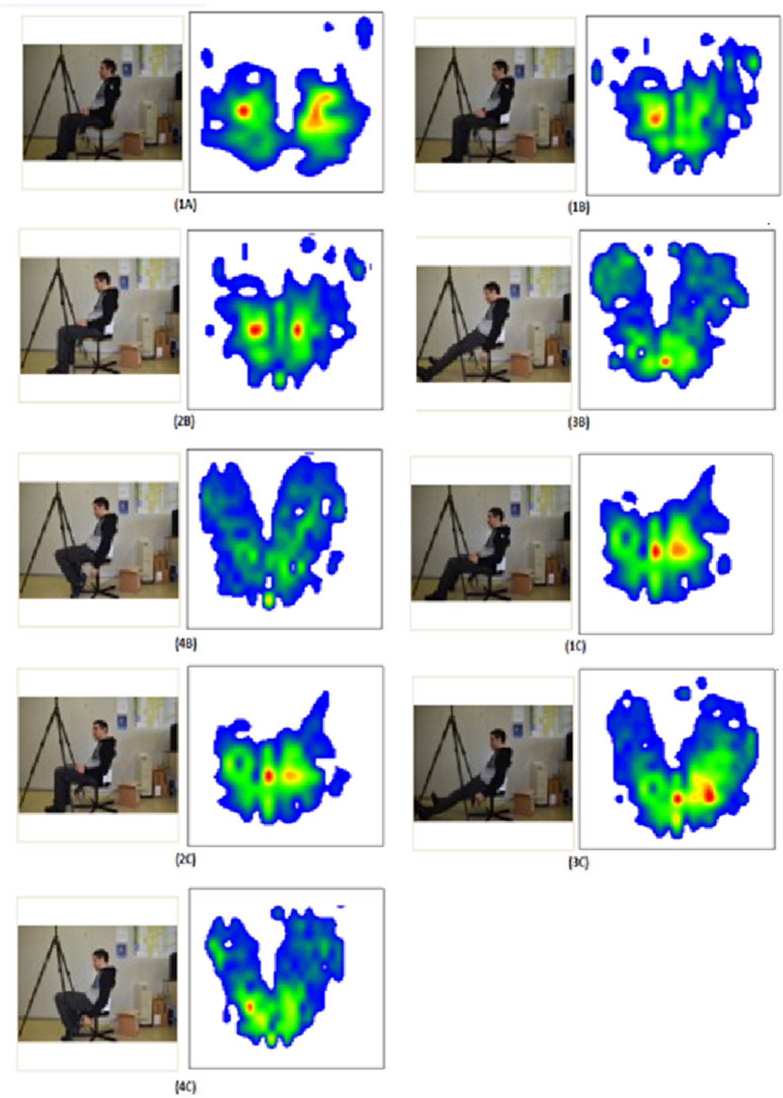

Fig. 7.4: An example of the nine postures with the relative pressure distribution maps

7.3.4 Collected Data

Three kinds of data were collected for each of the positions: pressure distribution at the interface; posture measurements; and level of discomfort associated with the pressure distribution. The body pressure distribution was also recorded for each position, and the 24x20 matrix of sensors was divided as shown in Fig. 7.5.

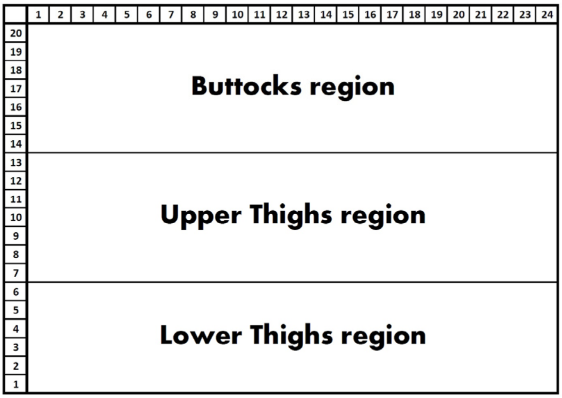

Fig. 7.5: Pressure pad regions

From the pressure matrix, the following calculations were performed for the buttocks, the upper thighs, and the lower thighs:

- peak pressure (Pmax) [N/cm^2];
- average pressure (Pmean) [N/cm^2];
- contact area (Area) [cm^2].

Postural data was taken from photographs processed using Kinovea® software. The postural angles were (see Fig. 7.6):

- trunk flexion (TF): the angle between the line across the acromion and the greater trochanter, and the vertical line across the greater trochanter;
- thigh flexion (tf): the angle between the line joining the head of the humerus and the knee, and the line perpendicular to the floor;
- leg flexion/extension (lf): the angle between the extension of the line joining the head of the humerus and the knee, and the line joining the knee and the ankle;
- thigh abduction (ta): the angle between the midline of the body (in the frontal plane), and the line passing through the centre of the thigh;

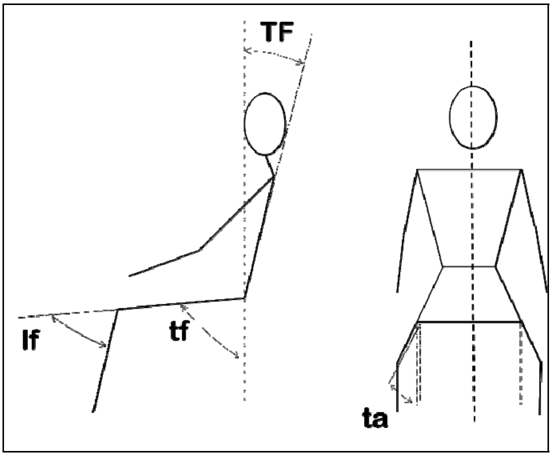

Fig. 7.6: Angles shown on a biomechanical model in the sagittal (left) and frontal (right) planes

At the end of the test, each subject was asked to complete the discomfort questionnaire for each region of their buttocks for the positions (1A), (1B) and (1C). To obtain a general (dis)comfort index, the averages for both the left and right areas were taken.

The values used by the questionnaire to record the pressure sensation (and the related Index of (dis)comfort (IC)) are shown in Table 7.2.

😁	No discomfort	2
😊	Position pleasant enough	1
😐	Neither comfort or discomfort	0
😣	Strongly localized pressure on the seat/ Strongly localized discomfort	-1
😡	Much pressure on the seat / Extreme discomfort	-2

Table 7.2: Index of (dis)comfort (IC) for each item of the questionnaire

7.4 Data analysis

Table 3 shows the mean values of the postural angles, IC, and pressure indices for the different postures. To distinguish the effect of postural discomfort from perceived discomfort due to pressure distribution, the IC is only given for the correct (most comfortable) postures (1A, 1B and 1C).

	(1A)	(1B)	(1C)	(2B)	(2C)	(3B)	(3C)	(4B)	(4C)
	Mean Value	Mean Value	Mean Value	Mean Value	Mean Value	Mean Value	Mean Value	Mean Value	Mean Value
TF	3.39	2.88	3.48	2.97	3.88	2.14	2.32	2.52	3.04
Tf	2.79	2.79	3.55	2.80	3.70	2.42	2.64	2.60	3.43
Lf	0.26	0.37	0.30	0.33	0.15	1.32	1.03	0.96	1.12
Ta	1.15	1.01	1.25	1.06	1.32	0.88	1.02	0.88	1.14
Pmax buttocks	0.67	0.64	0.93	0.70	1.06	0.88	1.02	0.88	1.14
Pmax upper thighs	0.11	0.17	0.13	0.15	0.06	0.75	0.77	0.75	0.94
Pmax lower thighs	125.41	120.52	111.04	124.59	112.69	88.96	102.85	111.63	101.85
Pmean buttocks	167.63	203.63	135.78	198.81	110.31	241.48	223.46	228.30	163.15
Pmean upper thighs	28.74	32.93	27.70	34.37	17.08	86.00	72.62	78.89	77.15
Pmean lower thighs	12.70	13.26	13.96	13.30	14.27	14.63	16.31	12.07	14.35
Area buttocks	83.89	84.30	88.74	81.15	93.69	77.04	75.58	78.22	83.62
Area upper thighs	78.56	85.67	85.15	66.33	92.58	57.04	23.54	111.52	126.38
Area lower thighs	5.96	6.00	4.15	2.22	3.31	0.81	-0.92	1.48	3.35
IC buttocks	0.63	0.46	0.22						
IC upper thighs	0.91	0.78	0.67						
IC lower thighs	1.61	1.37	0.87						

Table 7.3: The mean values of pressure, postural factors and IC index for the different postures

Data were gathered to evaluate the impact of the pressure distribution at the interface (Pmax, Pmean and Area of Contact) on the individual characteristics of the subjects (age, gender, height, weight and BMI), on the posture (trunk flexion, thigh flexion, leg flexion/extension, thigh abduction) and on the perception of (dis)comfort (IC). A multivariate analysis was performed to verify the possible correlations among the variables using SPSS rel.16 software. Pearson correlation coefficients were calculated to determine the strength of the relationships between all the variables.

7.5 Results and discussion

The multivariate analysis revealed several significant correlations among the variables, principally:

- Positive correlations between anthropometric variables and pressure variables: Pmax increases with subjects' height and age; Pmean increases with subjects' height and weight;
- Negative correlation between the contact area and Pmax: Pmax decreases as the contact area increases.

In the second part of the study, correlation analysis was performed on the three separate areas of the buttocks. The aim was to evaluate possible correlations between pressure and postural data. A summary of the analysis is shown in Table 7.4.

		tf	lf	ta	TF
Buttocks	Pmax	r = 0.192**		r = 0.147*	
	Pmean	r = 0.221**		r = 0.184**	
	Area				r = -0.352**
Upper thighs	Pmax	r = 0.191**	r = 0.175**	r = 0.369**	
	Pmean	r = 0.168**	r = 0.257**	r = 0.148**	r = 0.296**
	Area	r = -0.296*	r = -0.136**		
Lower thighs	Pmax	r = -0.364**		r = -0.190 **	
	Pmean	r = -0.434**	r = -0.227**	r = -0.198**	
	Area	r = -0.428**		r = -0.135**	

*. Correlation is significant at the 0.05 level; **. Correlation is significant at the 0.01 level

Table 7.4: Values of correlation

Further analysis was carried out on results relating only to postures (1A), (1B) and (1C) for which subjects gave a judgment on their perceived (dis)comfort. The Pearson index revealed a strong positive correlation between the contact area and the IC for the buttocks (correlation is significant at the 0.01 level) and the upper thighs (correlation is significant at the 0.05 level): the IC increases in line with the contact area. However, no correlation was observed between the middle contact area and the IC.

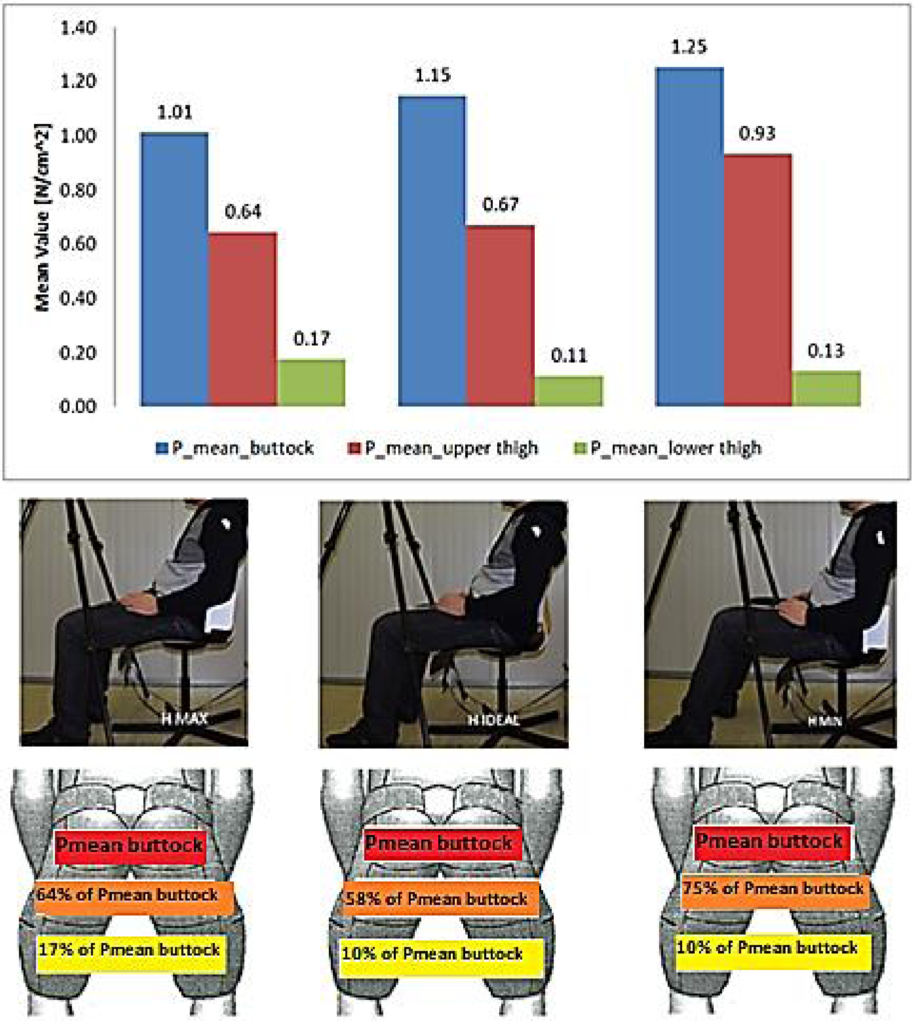

Fig. 7.7: Mean pressures at the interface between body parts and seat

For postures (1A), (1B) and (1C), the subjects were asked to assume the most comfortable position. For postures (1B) and (1C), the seat was adjusted to its maximum and minimum height, respectively. In posture (1A), subjects were left to determine both the most comfortable posture and the ideal seat height. The IC was highest in the latter (1A). The aim here was to examine how this finding related to pressure values. Fig. 7.7 shows that the mean pressure values were intermediate in the ideal position (1A), compared with the other two positions ((1B) and (1C)). The percentage in Fig. 7.7 is referred to the maximum value of Pmean that is always located in the buttock area.

The distribution of the load on the body parts in contact with the chair provides another relevant result. Due to the fact that load distribution depends on average pressure and contact area, the results shown in Fig. 7.8 are different from those in Fig. 7.7:

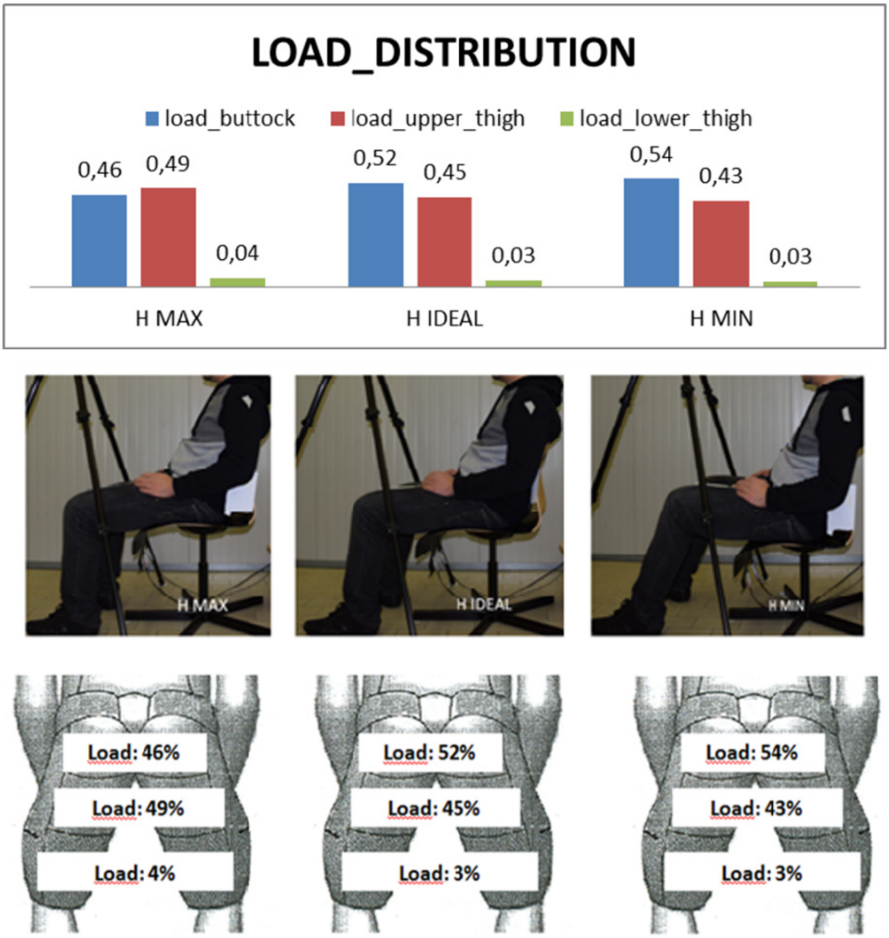

Fig. 7.8: Distribution of the load on the body parts in contact with the seat

Similar analyses have been previously carried out to discover the ideal load distribution in a car seat (Hartung [34]). This research was then taken up by Zenk to verify whether the stated ideal pressure distribution resulted in lower intervertebral disc pressures (Zenk [13]). In the present study, the ideal position – where subjects are requested to assume their most comfortable posture – gives a pressure distribution of 60-35-5 (buttocks, upper thighs, lower thighs) and a load distribution of 52-45-3 (buttocks, upper thighs, lower thighs). These results differ from those of Zenk [13], for which the ideal load distribution – in this case for a car seat – is shown in Fig. 7.9.

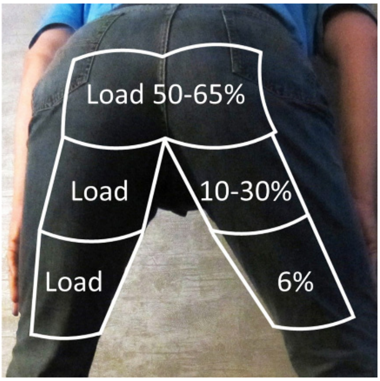

Fig. 7.9: Load distribution of body parts in contact with a car seat in Zenk, 2012

The difference between Zenk's results and those of the present study is due to the former involving a soft, padded seat on which the subject assumed a specific posture. Both the seat and the assumed postures in the present study were entirely different. Furthermore, the posture in Zenk's study was held for two hours, while in this study, the perceived discomfort has been examined after just five minutes.

The most interesting results produced by these analyses are those showing that discomfort due to pressure and load are perceived differently. Pressure, which acts directly on the skin and the soft tissue, gave a perception of discomfort derived from physiological and tactile sensations; load distribution, meanwhile, which affects the configuration of the body's forces (in effect, its entire equilibrium), gave a perception of discomfort perception derived from physical and postural effects. This finding is also validated by the fact that the minimum discomfort is perceived for different configurations of loads and pressures.

Finally, the results of the present study verify the above-mentioned hypotheses (Hi) as follows:

- H1: In agreement with the study by Zenk et al. [13], the greatest pressure was found in the buttocks area due to the weight of the torso. Loads were equally distributed across the buttocks and the upper thighs;
- H2: Data revealed that heavier people have a larger contact area with the rigid seat, as for the study by Vink [31];
- H3: Data revealed that taller people in the minimum seat-height position experience more pressure on the front of their thighs. This result is comparable to that of a study by Zenk et al. [13];
- H4: The Pearson index revealed a strong positive correlation between the contact area and the IC, as demonstrated in Hiemstra-van Mastrigt [33];
- H5: Data revealed that there is always a correlation between anthropometric measures and pressure factors, as stated in Hiemstra-van Mastrigt [33].

The most relevant result comes from the different ways that pressure distributions and load distributions are perceived. The analyses revealed that pressure distribution affects perceived physiological and tactile (dis)comfort, while load distribution affects perceived postural and physical (dis)comfort.

A limitation of this study may be the duration of the test (only five minutes for each posture), which may well affect the perception of (dis)comfort – in particular (dis)comfort due to physiological effects such as constricted vessels or ad tactile feeling on the skin. Furthermore, even if we know that the effect of the backrest and its interaction with subjects' back can influence the body posture and the (dis)comfort perception, we were able to neglect this effect because all subjects were asked to put their back on the backrest, and they did that.

Further interesting data might be acquired by taking into account also the temperature at the interface between the legs and the chair, and by monitoring the evolution of (dis)comfort over time.

7.6 Conclusion

A factor influencing the perception of (dis)comfort in HMI is the pressure distribution of the body – or a part the body – in contact with an object. In the present study, this involved the interaction between a rigid seat and the buttocks and thighs of a sitting subject.

The specific aim was to investigate not only the pressure variables but also the correlations between acquired pressure, personal characteristics, postural configuration and subjective perceptions of (dis)comfort. This was achieved via the gathering of several types of data, including gender, weight, height and BMI; trunk flexion, thigh flexion, leg flexion/extension and thigh abduction; IC; and Pmax, Pmean and contact area.

Using the Pearson index, statistical analysis revealed positive correlations between the anthropometric variables and the pressure variables; a negative correlation between the pressure variables; positive correlations between the pressure variables and the postural variables; and a positive correlation between the IC and the contact area.

A comparison of results of the present study and those of Zenk [13] reveals several differences due to the different methodologies employed (seat type and sitting time)..

7.7 Acknowledgement

The tests in the present study were performed in the virtual reality laboratory (VRLab) of the Department of Industrial Engineering at the University of Salerno, Italy. We extend our thanks to the third- and fifth-year mechanical and management engineering students (2016), who gave us their time and patience during many hours of testing.

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Chapter 8

Comfort-driven design of car interiors: a method to trace iso-comfort surfaces for positioning the dashboard commands

8 Comfort-driven design of car interiors: a method to trace iso-comfort surfaces for positioning the dashboard commands

8.1 Summary

General comfort can be defined as the measure of the “level of well-being” perceived by humans when interacting with a working environment. The state of the art for comfort/discomfort evaluation shows the need for an objective method to evaluate both “effects on the internal body” and “perceived effects” when considering the perception of comfort.

Medical studies show that each joint has its own natural resting posture. In this posture, the human-body muscles are completely relaxed or at minimum levels of strain. The body’s geometrical configuration corresponds to the natural resting position of arms/legs/neck etc.

From this starting point, the authors experimented to develop and built postural-comfort curves for each degree of freedom (DOF) of upper-limb joints. These curves are regular, and do not show any kind of discontinuity. Software (CaMAN®) was developed to analyse different postures and calculate a postural comfort index for the entire upper body.

This study examines a postural comfort study that has been used to develop the MATLAB® Digital Human Model. Several routines for tracing trajectories while reaching for commands in a confined environment (e.g., a work table or a car-cockpit) were evaluated to obtain the maximum perceived postural comfort for each target point. Iso-comfort points were defined for each space, and iso-comfort surfaces were designed using an appropriate CAD system. An example of these routines is shown below.

Iso-comfort surfaces can be also customized for different percentiles. This allows car-interior designers to have a virtual knowledge of the final perceived comfort when they decide, for example, on the positioning of a dashboard command.

8.2 Introduction

The knowledge described in previous chapter two, three and four has been used to develop an application for assessing the upper limb postural comfort during the early stage of a car-cockpit design.

In the NC-Model (Naddeo et al. [1]), this kind of application is placed into the frame “perceived effect due to posture configuration” without applying loads.

Some medical studies show that each joint has its own natural resting posture [2,3]. In this posture, muscles are completely relaxed or at minimum strain levels. The geometrical configuration corresponds to the natural resting position of arms/legs/neck and other joints. This position seems to minimize MSD and optimize the perception of comfort [4]. In Apostolico et al. [5] the problem of identification and use of resting posture concepts in ergonomics/comfort evaluations has been faced and a new method for an objective evaluation of internal body effects (such as body posture and muscle activation) and of perceived effects on several body parts, based on “range of rest posture” (RRP), has been proposed.

In Naddeo et al. [6], a new method for evaluating the perceived comfort for upper limbs was proposed according to these hypotheses. Software (CaMAN®) was also developed for the easy calculation of postural comfort ratings.

8.3 The aim of this research

In recent years, car manufacturers have directed their research efforts towards improved design in terms of safety, the environment, consumption, lightweight [7], and aesthetics. Several R&D instruments and methods have been developed to attain the best performances at the virtual prototyping stage (early design stage). Nowadays, research on comfort, especially on physical and psychological factors affecting perceived comfort levels of drivers when interacting with commands, has become of primary interest for car designers and manufacturers [8].

This work analyses the postural aspect of perceived comfort when driving a car. The main focus is on perceived comfort when reaching for and using a dashboard command. The study was performed using a MATLAB® Digital Human Model, and several routines for tracing trajectories when reaching for commands within the confines of a car cockpit.

8.4 The MATLAB® Digital Human Model

The basic idea is as follows:

- to create a model based on a simplified human-scale manikin, capable of reproducing a wide range of postures;
- to create functions (from the available information) that associate a degree of discomfort to the position of each joint;
- to add up the comfort levels for each joint using the CaMAN® software, and to obtain an overall postural comfort value.

The simplified manikin was modelled and developed in Solidworks® to reproduce, via a parametric/variational CAD model, the 50th percentile for male and female body types. Segments lengths are easily modifiable, allowing the manikin to be scaled to a different percentile.

The simplified manikin is composed of solid segments and 14 joints (Fig. 8.1), which simplifies movement as follows:

- Neck:
    - frontal bending
    - lateral bending
    - rotation
- Shoulder
    - flexion/extension
    - abduction/adduction
    - internal/external rotation
- Elbow
    - bending
- Wrist
    - ulnar/radial deviation
    - abduction/adduction
    - internal/external rotation
- CG
    - frontal bending
    - lateral bending
    - rotation
- Hip
    - flexion/extension
    - abduction/adduction
    - internal/external rotation
- Knee

    - bending
- Ankle
    - dorsal/plantar flexion

Inversion/eversion (a complex movement that is managed as the sum of two simple rotations)

After the calculation of the DOF for each joint, it was stated that the manikin has 30 DOFs.

Next, the length of the segments was determined in a parametric manner. Every body type was represented, according to the European human-scale criteria of sex and height taken from Dassault-Systemes' DELMIA® database.

After modeling all of the geometric features using the MATLAB® software, the first version of the manikin was created as a multi-body system governed by a series of angles.

This model was interfaced and mathematically modelled by MATLAB® Simulink (Fig. 8.2) using SimMechanics® as importing software. The final MATLAB® model was refined in order to include the correct ROMs for each joint.

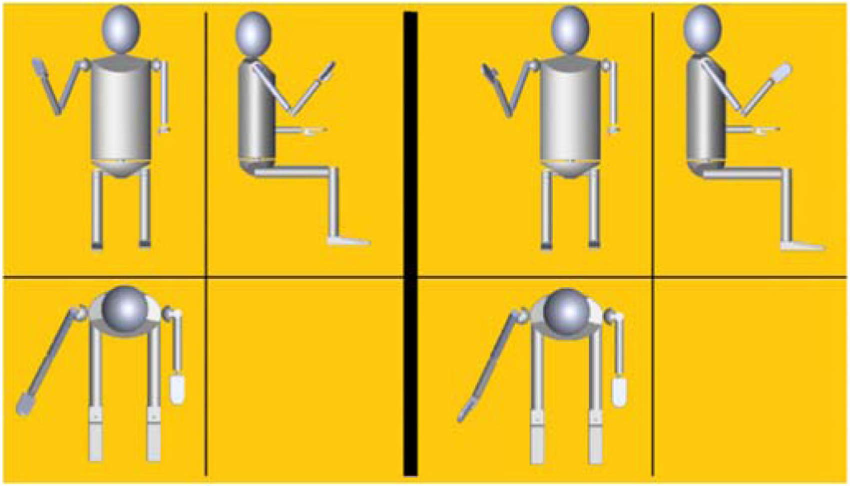

Fig. 8.1: Solidworks® Model

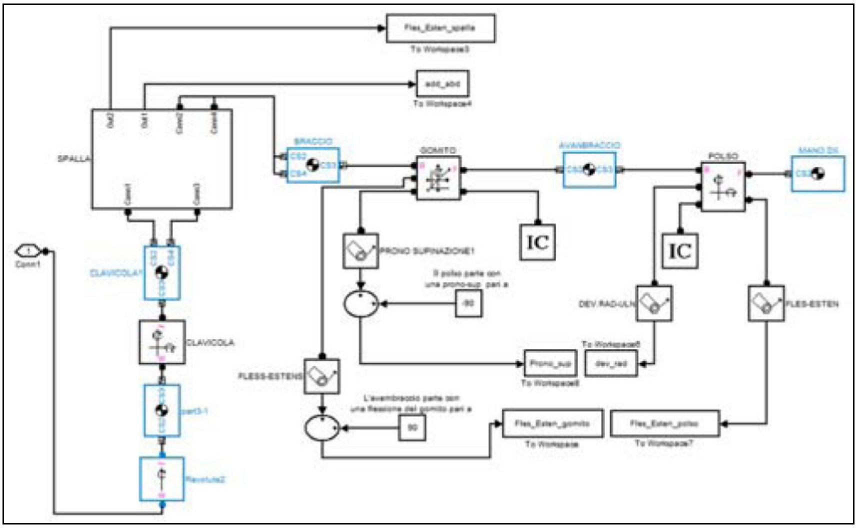

Fig. 8.2: Example of Shoulder model in MATLAB® Simulink

The whole-body model of the manikin was directly interfaced with CaMAN® software, allowing for a quick postural analysis. Calculations of perceived comfort were very easy to perform.

Description of routines for tracing trajectories and iso-comfort curves

A pilot study was performed on the right arm according to the following hypotheses:

1) The manikin is in the seated position, as is the case for every car driving experience.
2) The chest is always rigid from the hip (no torsion or flexion around the hip are allowed). This hypothesis allows to simulate and evaluate the comfort of the subject's upper limbs without altering their chest position. It also allows to exclude the influence of hidden spinal MSDs that can be revealed during testing.
3) The initial position is always defined as: elbow flexion = 90°; pronation/supination of the arm = -90°; all other angles = 0°; hand in horizontal position (parallel to the ground). This position has been chosen for two reasons: first, because it represents a position very close to that of the real-life driver; second, because the combination of angles is closest to the minimum muscular-activation position (best perceived comfort).
4) All movements made by the manikin for reaching a specific point proceed as follows:

- The longitudinal axis of the forearm is moved towards the chosen point, moving only the shoulder joint;
- All the other angles of the arm joints are evaluated by solving the Inverse Kinematics Chain Problem.

This choice was made because results of the broad experimental test-phase (involving about 100 subjects) revealed this to be a systematic pointing behaviour. The majority of subjects, regardless of gender and anthropometric measures, moved their upper limbs in this order (shoulder first and then the other joints). Similar behaviour has been detected in previous research on pointing movement strategies [9].

5) Reference axes (Fig. 8.3) are positioned with a vertical Z-axis. Each Z-value identifies a horizontal plane (parallel to the ground) in which the reachable points are ordered in a grid whose origin (X=0 and Y=0) is positioned in the centre of the shoulder joint.

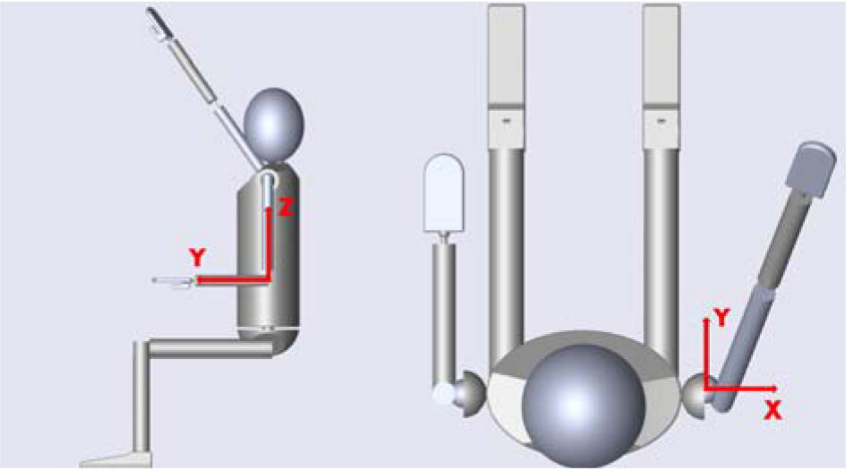

Fig. 8.3: Reference axes

The procedure is based on three routines developed in MATLAB®.

The function of the first routine is to identify a set of reachable points in the 3D space behind the subject, and to check and automatically evaluate the perceived comfort corresponding to the angle of the joints. First, the routine creates an ordered cloud that represents all of the reachable points in an environment. The distance between these points, (i.e. the resolution of the grid) can be chosen by the user. For each point, a subroutine then creates a complete "design of experiment" (DOE) of all possible angle combinations for the joints, and checks how many of these are compatible with the chosen target point. Subroutine constraints are represented by the ROM limits for each joint [10-12,15]. The outcome of this routine is the set of reachable points and, for each point, a discrete set of possible joint configurations that allows the desired position to be reached with the second finger of the right hand. The CaMAN® interface calculates a comfort value for each of these configurations.

The second routine extracts the body configuration in which the best value of perceived comfort when reaching a given point was found. These results are ordered in a 3D matrix.

The third routine analyses the comfort values for the point of each Z-plane, and traces a curve that represents the maximum comfort values. A specific subroutine for a given plane (Z-value) and a given X-value creates an interpolation curve (Spline curve) "Y -vs- Comfort-Rating" that allows to identify, for example, a reachable position whose comfort rating is specified by a designer.

Using the third routine, designers can choose a comfort target-value and identify a cloud for each point that represents the iso-comfort surface.

8.5 Test case description

In [13], Naddeo et al. carried out a study examining the correlation between perceived postural and global comfort. This study was based on their wide-ranging experimental work on the FIAT "Grande Punto" dashboard. It analysed a set of 36 subjects (24 male and 12 female) and tested the following four areas:

1. Steering wheel (test performed taking into account shoulder flexion, elbow flexion, wrist radio-ulnar deviation and neck frontal flexion);
2. Gear shift (test performed taking into account shoulder flexion, elbow flexion, wrist radio-ulnar deviation and neck frontal flexion);
3. Volume control (test performed taking into account shoulder flexion, elbow flexion, wrist radio-ulnar deviation and neck frontal flexion);
4. Air conditioner control (test performed taking into account shoulder flexion, shoulder abduction, elbow flexion, wrist radio-ulnar deviation and neck frontal flexion);

Each of these tests involved 36 couples (each one formed by these two comfort indexes: global and postural) who together made up the comparison.

In the present work, the postural results obtained in [13] have been used to check and validate the proposed method for tracing iso-comfort curves.

A 50th percentile male manikin was chosen to perform the procedure test. Solidworks® allowed the manikin to be easily scaled to the required measurements, and, through the use of SimMechanics®, the human model and its joints were "charged" in MATLAB® software.

8.6 Results and discussion

The results in terms of mean perceived comfort for these routines are shown in Fig. 8.4 and Fig. 8.5.

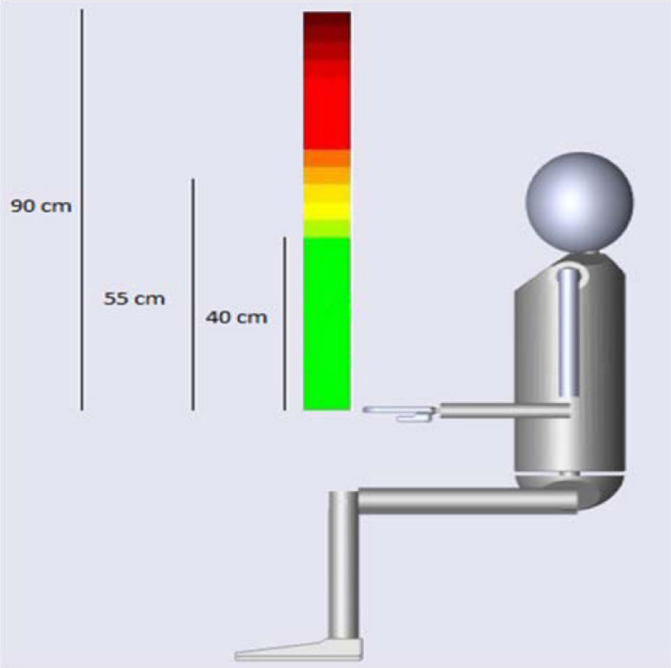

Fig. 8.4: Graphical representation of perceived comfort –vs- height

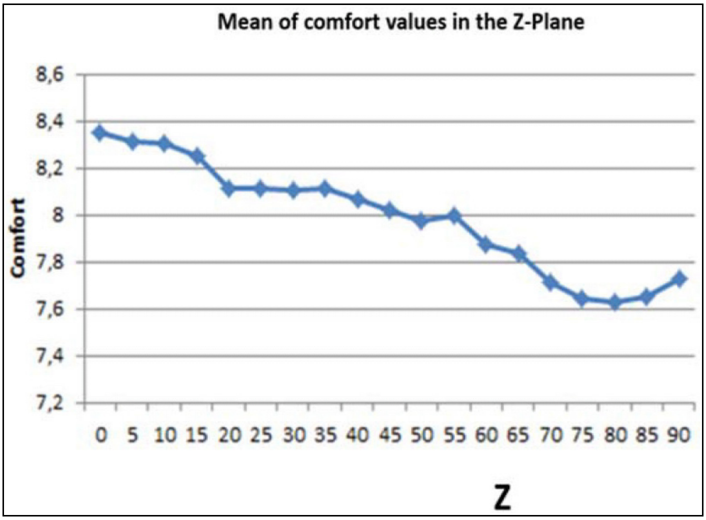

Fig. 8.5: Mean of perceived comfort towards height of the point to reach

The plane-by-plane results, in terms of points of maximum perceived comfort, are shown in Figures 5.8 to 5.15.

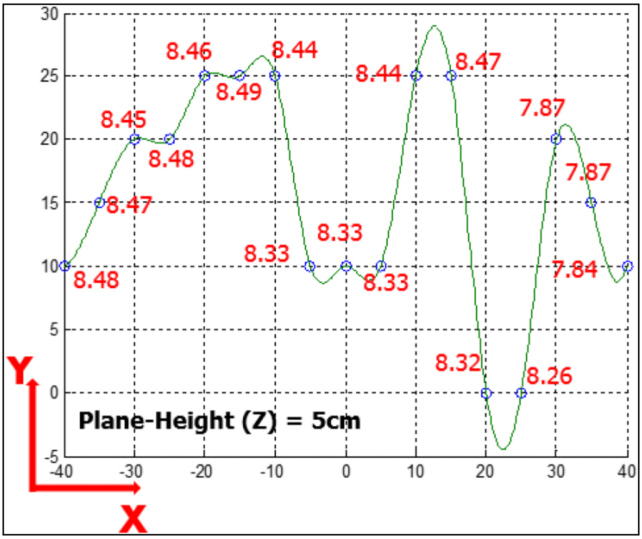

Fig. 8.6: Maximum postural-comfort values (in red) for different XY positions, Z = 5 cm

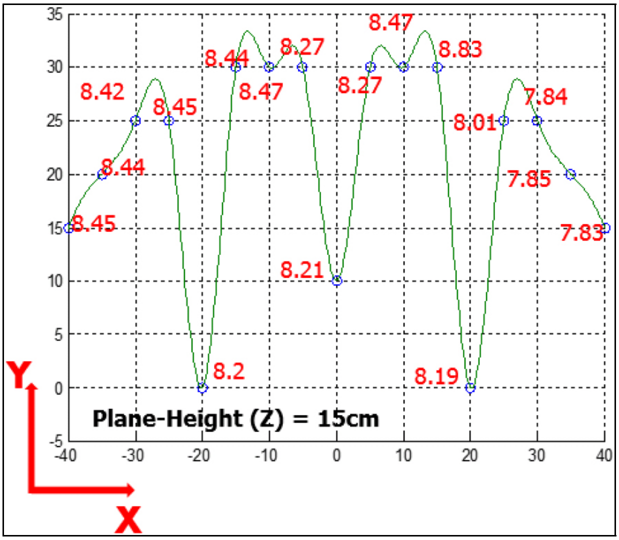

Fig. 8.7: Maximum postural-comfort values (in red) for different XY positions, Z = 15 cm

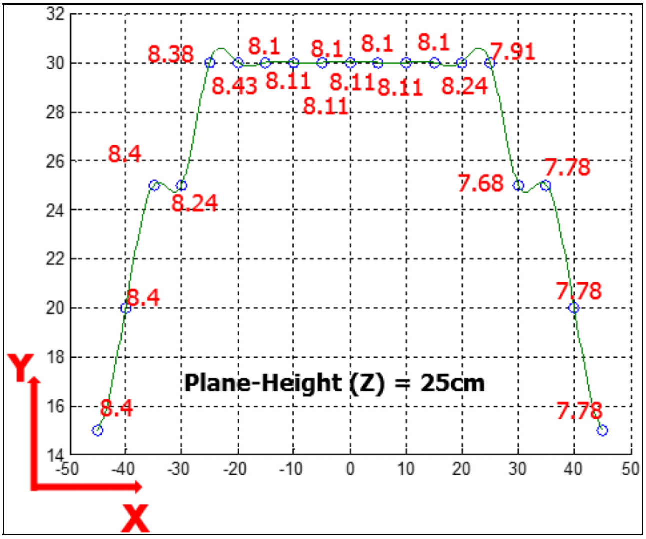

Fig. 8.8: Maximum postural-comfort values (in red) for different XY positions, Z = 25 cm

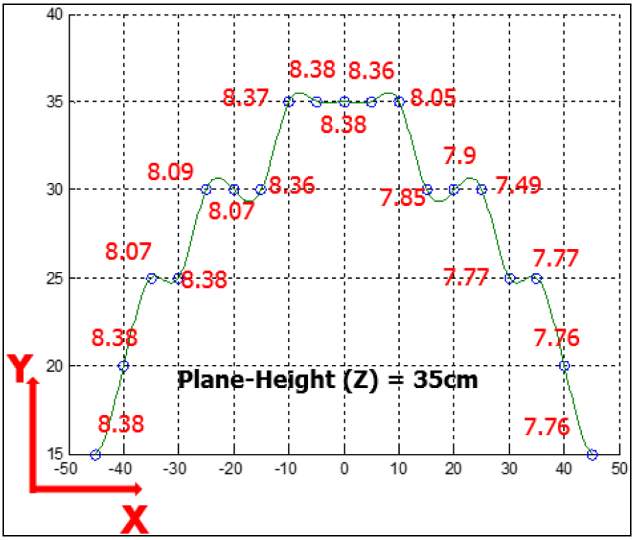

Fig. 8.9: Maximum postural-comfort values (in red) for different XY positions, Z = 35 cm

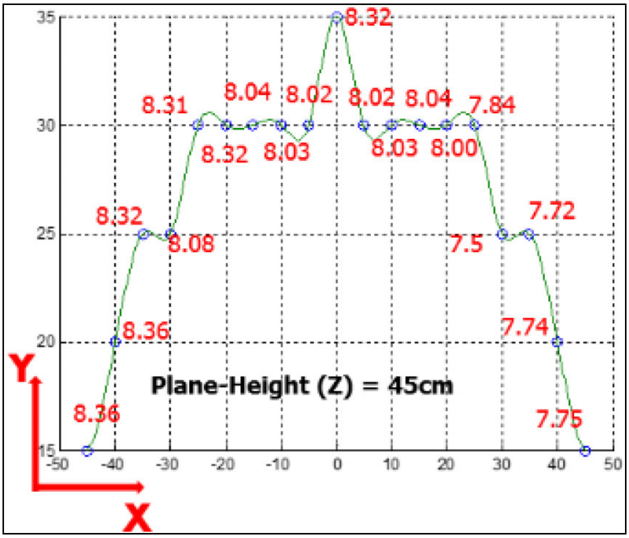

Fig. 8.10: Maximum postural-comfort values (in red) for different XY positions, Z = 45 cm

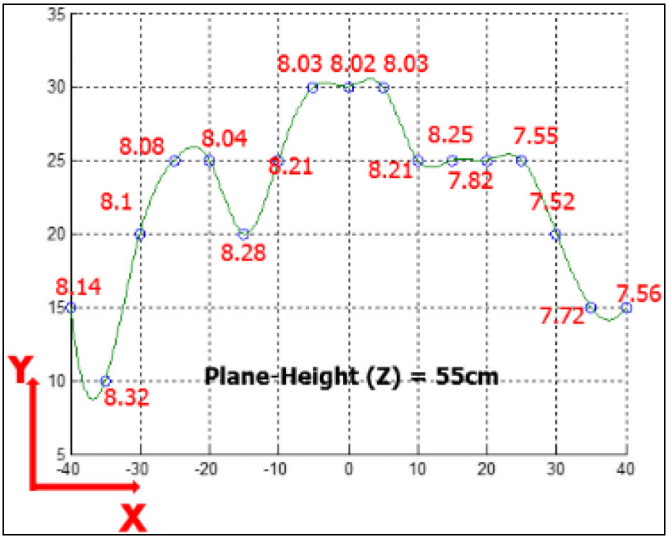

Fig. 8.11: Maximum postural-comfort values (in red) for different XY positions, Z = 55 cm

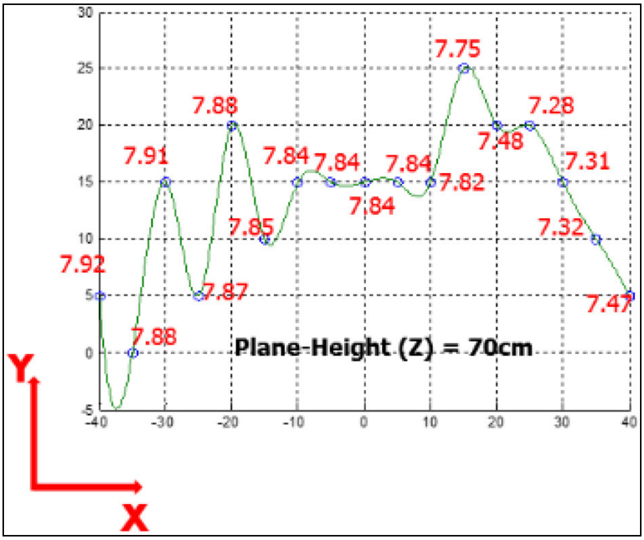

Fig. 8.12: Maximum postural-comfort values (in red) for different XY positions, Z = 70 cm

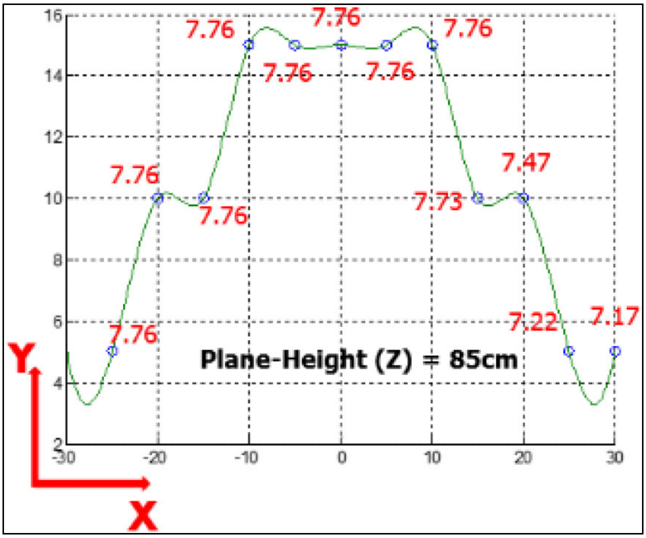

Fig. 8.13: Maximum postural-comfort values (in red) for different XY positions, Z = 85 cm

The results show that the higher the target point to reach, the worse the perceived level of comfort is (green=good, red=bad). However, the comfort rating improved in the highest planes (80-90 cm). This can be explained by the fact that when reaching for the highest positions, the arm's centre of gravity is closer to the body and muscular activation decreases.

Results obtained using the MATLAB® manikin (Fig. 8.14) and the CaMAN® routine (Fig. 8.15) were compared with experimental results (Fig. 8.16 – [13]) obtained by questionnaire and by comfort rating using the same software (CaMAN®). All tests showed the same results (with a maximum error of about 5%) for the software used in this study.

DELMIA analysis (Fig. 8.17) was conducted as well to test and verify the studied postures.

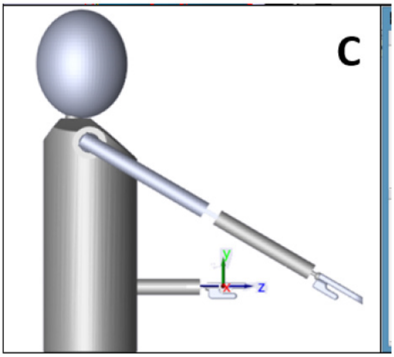

Fig. 8.14: Solidworks®/MATLAB® Human Model

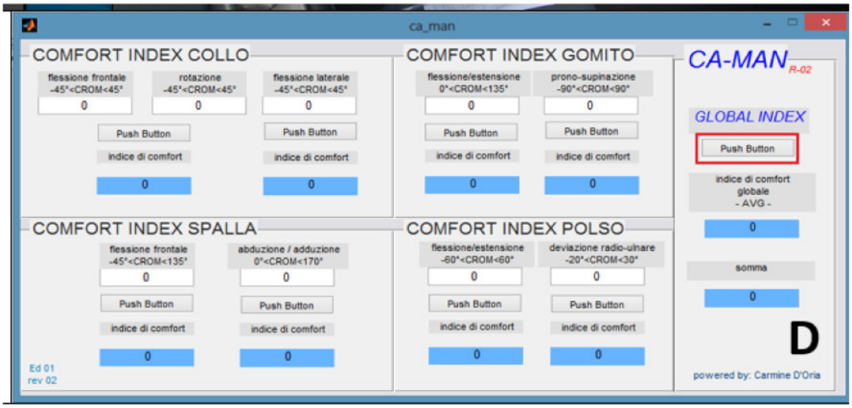

Fig. 8.15: CaMAN® software interface

Fig. 8.16: Experimental test

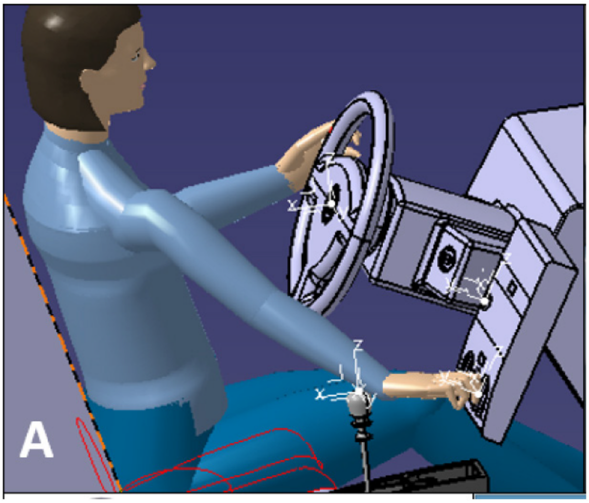

Fig. 8.17: DELMIA® simulation

The routine can be easily used to re-design the acquired/analysed dashboard to position commands for optimal perceived comfort. The experiments (Figures 8.14, 8.15, 8.16 and 8.17) can be easily reproduced to verify tests results.

The details about comparisons between the three results (Delmia, the proposed method and the subjects' responses) have been omitted for paper-size reason. As told before, the percentage error between CaMAN® evaluations and subjective evaluations was always within the 5% while DHM simulations with DELMIA® showed, for all tests, a very good numerical/Experimental correlation between the acquired postures and the simulated ones (Also within the 5% of error in terms of human joints' angles).

8.7 Conclusions

It was possible to create a model that was able provide the requisite assessments using a fully scalable manikin. Modelled in Solidworks®, this manikin was able to represent all percentiles of male and female body types. Then, a software allowing to easily analyse the following three aspects of ergonomics and comfort was developed:

1) Analysis of reachability;
2) Analysis and individuation of the best configuration of joints, in terms of perceived postural comfort, for each reaching point;

3) Individuation of maximum comfort points and tracing of maximum comfort curves and iso-comfort surfaces.

The procedure also allowed to trace the best trajectory for reaching a single point. It could be easily used by designers for the individuation and positioning of devices that have to be used/actioned in car interiors. This could be performed very early on in the design process.

The Delmia performance in translating the postures' acquisition (through not invasive methods like the photographic one) in whole-body posture has been assessed in previous papers [6,12] and has been checked again in this work, giving very good results in terms of predictivity of DHM approach (less than 5% of error both in terms of Human Joints' angles and in terms of Comfort evaluation).

In addition, the model and accompanying software can be used in several kinds of working environment, as their functions do not depend on the object of interaction. The presence of obstacles and/or other devices can be easily taken into account by simply removing not-reachable points from the points' cloud when the reachability analysis is performed.

Future developments of the software may also take into account the cognitive and physiological aspects of comfort perception. This would be easy to implement using the current software, as it would only require that the "Target Function" is changed in the "Maximum Comfort Function".

The accordance between FCA in-Lab experiments and those performed in university laboratories – experiments involving both the in-house software (CaMAN®) and the software used for this study – was useful for validating the procedure.

8.8 Acknowledgments

The S.A.E. comfort evaluation system was provided by FIAT-Chrysler Automobile Research Centre in Naples. It was used for ergonomic and comfort evaluations in Seating-buck simulation. Experimental tests were performed in the virtual reality laboratory (VRLab) of the Department of Industrial Engineering at the University of Salerno, Italy, and in one of the external areas of the university campus. Both environments were opportunely set up to create optimal conditions for photographic acquisition. Many thanks to the students of last year's mechanical and management engineering class, who gave us their time and patience in carrying out many hours of testing.

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Chapter 9

Conclusions

9 Conclusions

9.1 Epilogue

In the Preface, starting with the thoughts of Stephen Hawking [1], the purpose of this PhD thesis has been described: the investigation and the look of a useful model to describe, analyse, evaluate and predict (dis)comfort perceptions.

The Introduction goes through the history of the design process, including developments with the new technologies of the digital era.

Among these developments, performance-driven design methods took us steps forward in terms of methodologies and technologies. Further, since 1990, the human-centered design [2,3] contributed greatly to the development of a user-centered approach [4] and, in general, to the study of human factors in design.

The research of models has been one of the engines propelling the work of sciences and scientists. Models have been developed for describing behaviours in a mathematical way. Physicians, naturalists, scientists and, of course, mathematicians have contributed toward helping humankind understand the behaviour of everything.

Nevertheless, human behaviour remains one of the most difficult notions to explain, both in terms of “human body reactions” and in terms of “brain mechanisms of understanding and interpreting body signals”.

In those areas, development of a model describing the (dis)comfort perceptions should be studied and understood. In the Introduction chapter, the literature demonstrates that several papers deal with models of perception but most are limited to one aspect of perception or to one specific kind of interaction.

The last 15 years have seen only five “comprehensive models” that considered every aspect of human perception: the Helander model [5], the Moes model [6], the Vink-Hallbeck model [7], the Naddeo-Cappetti model [8] and the Vink model [9].

The Vink model states that a general interaction that provokes a feeling of comfort, discomfort or nothing has been named the human-artefact-interaction (HAI); this acronym perfectly describes what happens in everyone’s daily lives.

In examining the thesis, it’s possible to recognize a journey that will drive engineers and designers to development of a general method for understanding and "decoding" human behaviour in terms of (dis)comfort perceptions during a HAI.

9.2 Main results

The main purpose of this PhD thesis can be summarised in these four research questions, stated in the first chapter [8,10]:

1) Can a comfort driven design method be developed and implemented in the products’ improvement process?
2) If so, what are the laws (νόμος) that allow the modelling of the (dis)comfort perception during an interaction? (Like user or, more generally, like human?)
3) Is it possible to develop a method to more objectively evaluate the (dis)comfort experience of humans?
4) What is the right research approach to define functions in the (dis)comfort equation?

In the successive eight chapters, several methods and examples were explored to achieve the goals of the thesis and provide the right answers to the research questions (Fig. 9.1).

In Chapter Two [11], the range of rest posture (RRP) – a new concept in human postural measurement that has proven of use for comfort evaluation – was introduced and described. The study focused on the identification of RRP within the comfort range of motion (CROM) for the following human joints: neck, shoulder, elbow, wrist and ankle. The work involved 85 healthy individuals (43 males and 42 females) ranging from 20 to 30 years old, targeting the experimental definition of CROM and the identification of RRP. The result was the definition of an easy method that, through experimental analysis and statistical evaluations, allows for identification of RRP in CROM of human joints; by this method, both RRP and maximum level of comfort (MLC) positions have been recognized. These positions were the foundations of the following studies that objectify postural comfort.

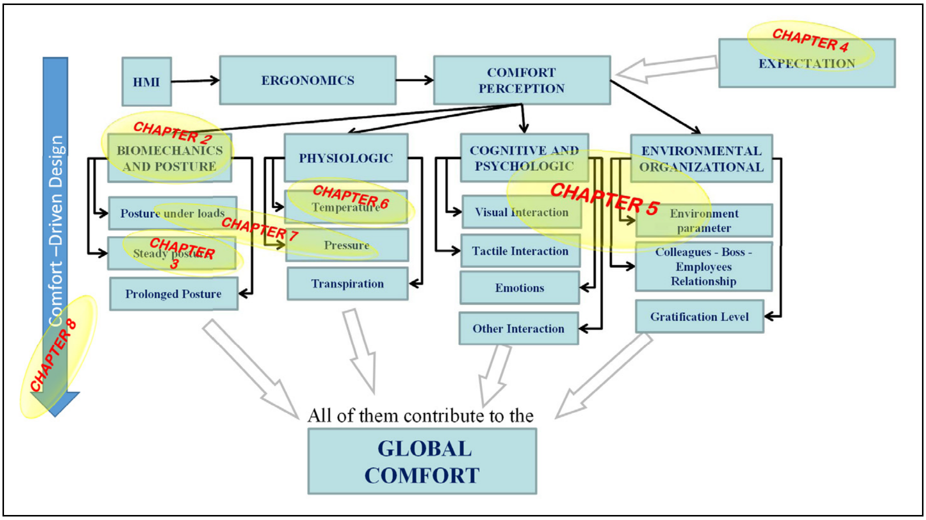

Fig. 9.1: Graphical summary of the Thesis work

In Chapter Three [12], a new quantitative method for evaluating the upper limbs' postural comfort (without applied loads) has been developed based on anthropometric parameters and upper limbs posture. The main targets of this research were:

- Development of an easy-to-use tool, named CaMAN®, for evaluating the perceived postural comfort for upper limbs;
- Explanation of an easy method – based on experiments on healthy people, statistical analysis, neural networks and data synthesis – for achieving the desired result: identifying curves that create perceived postural comfort of each human joint.

Chapter Four [13] presented the results of expectation influence analysis on comfort evaluation. Using the placebo effect, a wide experimental test-campaign with a wide sample of users was carried out. Participants were asked to use and evaluate two identical mattresses that were dressed and described as two different products (the first as a very cheap mattress and the second as a high-level expensive mattress). The differences between subjective evaluations were statistically processed and correlated to anthropometric parameters to individuate and understand the role of expectations.

The main results of these analyses were:

- As it was hypothesized by the Naddeo et al. [7] model, there is an indirect correlation between "expected comfort" and "perceived comfort";

- An increase of the expected comfort implied a decrease of the perceived comfort, and a decrease of the expected comfort implied an increase of the perceived comfort.
- Indirectly, it was also assessed that an increase of the expected comfort implied an increase of the perceived discomfort, and a decrease of the expected comfort implied a decrease of the perceived discomfort.

In Chapter Five [14], the Kansei technique was used as a comfort-evaluation tool to assess the individual and subjective emotional impressions of a car seat, where all senses of the consumer are involved.

The main results of the study were:

- The same object looked different if evaluated using different human-artefact level of interaction, from the interaction between a human and an image representing the artefact, to the interaction between a human (user) and the product into its normal environment (a car-seat inside a car). The effects of external and environmental factors on the perceived comfort have been assessed as very influencing factors.
- Kansei is an easy tool of investigation in cases of emotional evaluation and for understanding how environmental factors can affect interaction and, consequently, the perceived (dis)comfort.

In Chapter Six [15], one factor that influences physiological comfort perception has been investigated: the temperature difference between users and the objects with which they interact, as in the case of the human-mattress interaction.

The overall results of this study were the following:

- A temperature measuring system was designed in order to not affect the perceived comfort during temperature acquisition. This would override the problem highlighted in the NC-Model [8] regarding effects of an experimental device on subjects' (dis)comfort perception.
- It was used a 15-minute comfort evaluation time because a normal subject generally needs, in normal conditions, less than 15 minutes, in a steady posture, to begin to sleep. A lack of strong correlations between skin temperature changes and comfort perception changes was found.

- There was a correlation between the total increase of temperature at interface and the perceived comfort: The increase of temperature variation caused a reduction in comfort.

This study suggested that, when designing a new product for mattress manufacturers, the problem of interface temperature might have a minor priority over related issues, for example, with the acquired posture and the map of pressures. This is true since the temperature is always lower than “normal” skin temperature (about 37°C).

In Chapter Seven[16], a study of the combined effect of pressure, posture and load distribution on perceived comfort while seated was described. The specific aim of this study was to further investigate the impact of postural, personal and seat pan interface pressure on comfort factors. Personal factors of interest included gender, weight, height and BMI. Postural factors of interest were related only to the trunk and the lower limbs (thighs and legs).

The main results of this study were that pressure distribution and load distribution are perceived by subjects in different ways: the pressure distribution affects perceived physiological and tactile (dis)comfort due to a direct interaction with the “human sensors” belonging to the human skin and to the vessels, while load distribution affects perceived postural and physical (dis)comfort due to its influence on body balance and to the muscle-response of the whole body and, in particular, of the spine.

In the study, the experimental setup included a photographic acquisition system for postural analysis, which would override the problem highlighted in the NC-Model [8] regarding the effect of experimental devices (in this specific case, the tracking system tags) on subjects’ (dis)comfort perception.

Finally, Chapter Eight [17] presented an example of a comfort-driven target setting and the consequent comfort-driven redesign of a car’s dashboard, whose functional requirements were expressed by the phrase: ‘the HVAC regulation bolt has to be reached in a comfortable way by a car driver whose anthropometrics data are among the 5th female and the 95th male European percentiles’.

In this case study, the method for objectifying the postural comfort of the upper limbs, explained in Chapter Three [11], was used to determine the positioning of an automotive HVAC controls. The objectivised perceived postural comfort for the reachability and visibility of the controls were merged into an overall comfort function, optimised in terms of ‘ease of use’.

The results were a series of iso-comfort curves and surfaces that allowed the controls to be positioned to maximise predicted comfort. An example application on an FCA car was provided.

This work shows that it is possible to imagine a design method able to be followed by all people – scientists, researcher, designer, engineers, etc. – for studying one or more aspect of the (dis)comfort experience and investigating the relationships among design parameters (interaction characteristics) and functional requirements in terms of perceived (dis)comfort.

An example of a possible path defined by this thesis work is shown in the following Fig. 9.2.

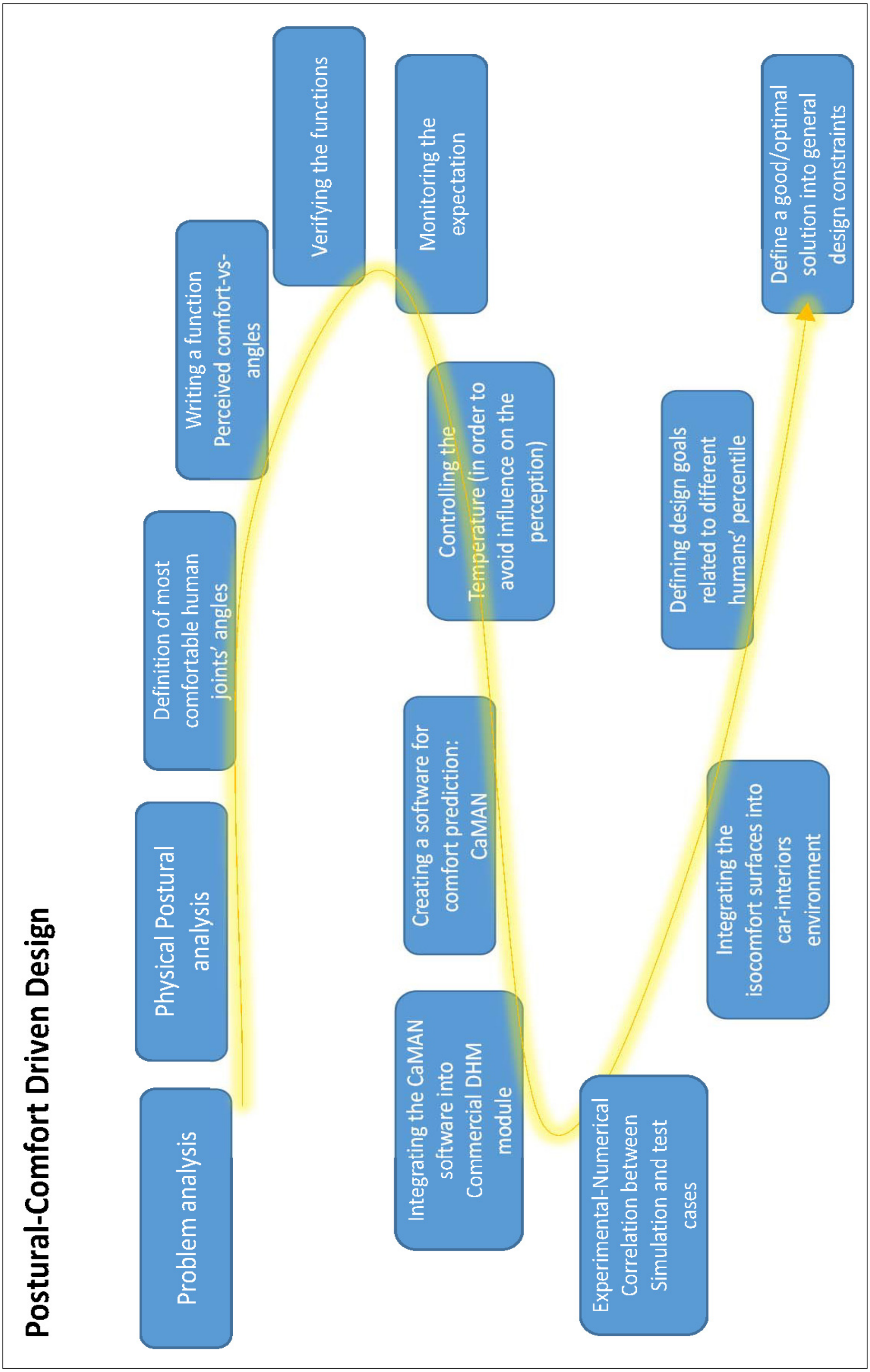

Fig. 9.2: A linear path for postural-comfort driven design

It is possible that the same path can be reproduced for each comfort-related performance that must be taken into account for specific interactions of the "perception model."

The thesis work provides answers to each research question asked in Chapter One.

9.3 Research questions' answers and limitations

1) Can a comfort driven design method be developed and implemented in the products' improvement process?

The answer is YES, it can!

A method to study comfort can be extracted directly from the general models of perception presented in the first chapter (the NC-Model [8] and the HAI model [9]). That chapter showed a matrix-based method [8] [14] for deploying the (dis)comfort issue for every kind of interaction that can be imagined. Based on that method, the approach to the problem can be easily individuated. Along the Comfort matrix, a designer/engineer can understand the main functional requirements to be studied and the main design parameters (product/process/ interaction characteristics) involved in the (dis)comfort perception. Furthermore, the designer can understand the primary elements affecting the perception and what modifiers can modify the perception itself. The right approach will, obviously, focus on primary elements and controlling (that is, trying to eliminate the influence) of modifier elements.

After the analysis of the problem through the comfort-matrix, a researcher can assess if there is sufficient knowledge in the literature on the focused problems and decide whether to use the results already researched or to develop his/her own research about the special issue or topic.

An evident limitation of this thesis work is that all the factors in the comfort matrix have been considered independent from each other, and the global comfort has been considered a linear combination of weighted factors. While a general validity cannot be upheld, for the first approach to this complex problem, it seems a useful way to conduct analyses and synthetize results.

2) What are the laws (νόμος) that allow the modelling of the (dis)comfort perception during an interaction? (Like user or, more generally, like human?)

Once the right way to approach a problem has been identified by the designers, they must assess if the available knowledge is sufficient to write a law, a function, a behavioural model and so on, for describing the (dis)comfort perception during an interaction. Also Vink (2014) [9] and Moes (2005) [6] describe some examples of laws in this way. However, the model of this PhD Thesis is more extensive and much work is needed to establish all relevant laws.

If the available knowledge is sufficient and is suitable for the specific design-case, the designer can use it for defining functions that allow prediction of the (dis)comfort perception before having a physical mock-up for reproducing the product/process/ interaction. If the knowledge is not available or suitable for the specific case, the designer must go to the answer to the fourth research question.

3) Is it possible to develop a method to more objectively evaluate the (dis)comfort experience of humans?

As every engineer usually replies to a complex question [18], the answer is: It depends.

The behaviour of the human body and its reactions to external stimuli is very complex (sometimes unknown [19]); thus, the answer seems to be "no". But that is not always true. New discoveries about how the body works have allowed us to understand the direct link between some human reactions (physiological parameters, skin parameters, joints' behaviour, etc.) and the consequence, in terms of perception, due to the elaboration of reactions in the human brain.

Several studies, cited in the previous chapters, have allowed us to write functions or draw some curves that explain the (dis)comfort perception related to a few (or at least one) physical parameter measured in the human body, like for instance the CROM or the relationship between seat pressure distribution and discomfort (de Looze et al., 2003) [20]. Once was written a model, an equation, a function or a curve describing a behaviour, there is the capability – in a controlled situation – to predict the perception by knowing all environmental factors that affect it (as explained in Chapter One [8]). This means that there is a method for more objectively evaluating or predicting the perceived (dis)comfort on the basis of the environment analysis (see Fig. 9.3).

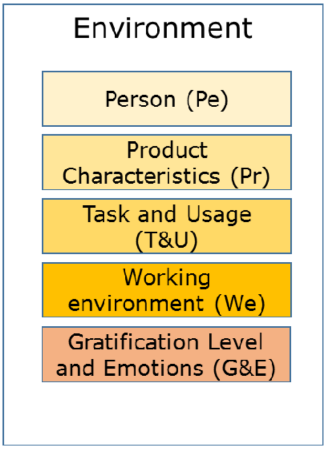

Fig. 9.3: Factors that determine the "environment" of an interaction

There are likely some perceptions that cannot easily be assessed through objective functions. In researchers' experience, often the experiments give bad results because of the impossibility to objectively assess a completely subjective experience [9,20]. This is recognized as another limitation of this thesis work: Within the chapters, nothing has been said about the factors (affecting perceptions) that can be objectivised (like prolonged posture influence or environmental factors) or the ones unsuitable for objective evaluation (like emotional status or the effect of psychological status during the experiments/interaction). This work on clustering the comfort-related factors might be the topic of future developments of the comfort matrix and the comfort equation.

Nevertheless, there are some comfort-related issues that can be faced through the right approach, as explained in the Chapters Two and Three.

This approach method can be represented in Fig. 9.4.

Following these steps, a designer/engineer/researcher can develop an equation/functions/curve to better predict the (dis)comfort perception for an interaction.

Finally, there is another aspect/limit that has to be taken into account while answering to the third question: performed studies, discussions and conclusions are often related to a specific targeted-user/test-subject group and cannot be upheld in general. Further studies can help us to try to widen as more as possible the percentage of a population to which a “more objective prediction” of perceived comfort can be extended.

4) What is the right research approach to define functions in the (dis)comfort equation?

As shown in the Chapter One [8], an equation describing the Comfort/Discomfort perception has been proposed based on the Comfort Matrix. It is useful to recall it:

$$C_i = Mod_C * P_C(h(Pe, Pr, T\&U, We, G\&E) - E$$
$$D_i = Mod_D * P_D(h(Pe, Pr, T\&U, We, G\&E) + E$$

In which:

Mod = Modifier of **P** (Perception) of the **h** = Human body effect due to:
Pe = Personal characteristics
Pr = Product characteristics
T&U = Task and usage
We = Activity environment
G&E = Gratification level and emotions
E = Expectations
Ci is one of the four kinds of Comfort: Postural, Physiologic, Cognitive&Psychologic, Environmental&Organizational
Di is one of the four kinds of Discomfort: Postural, Physiologic, Cognitive&Psychologic, Environmental&Organizational

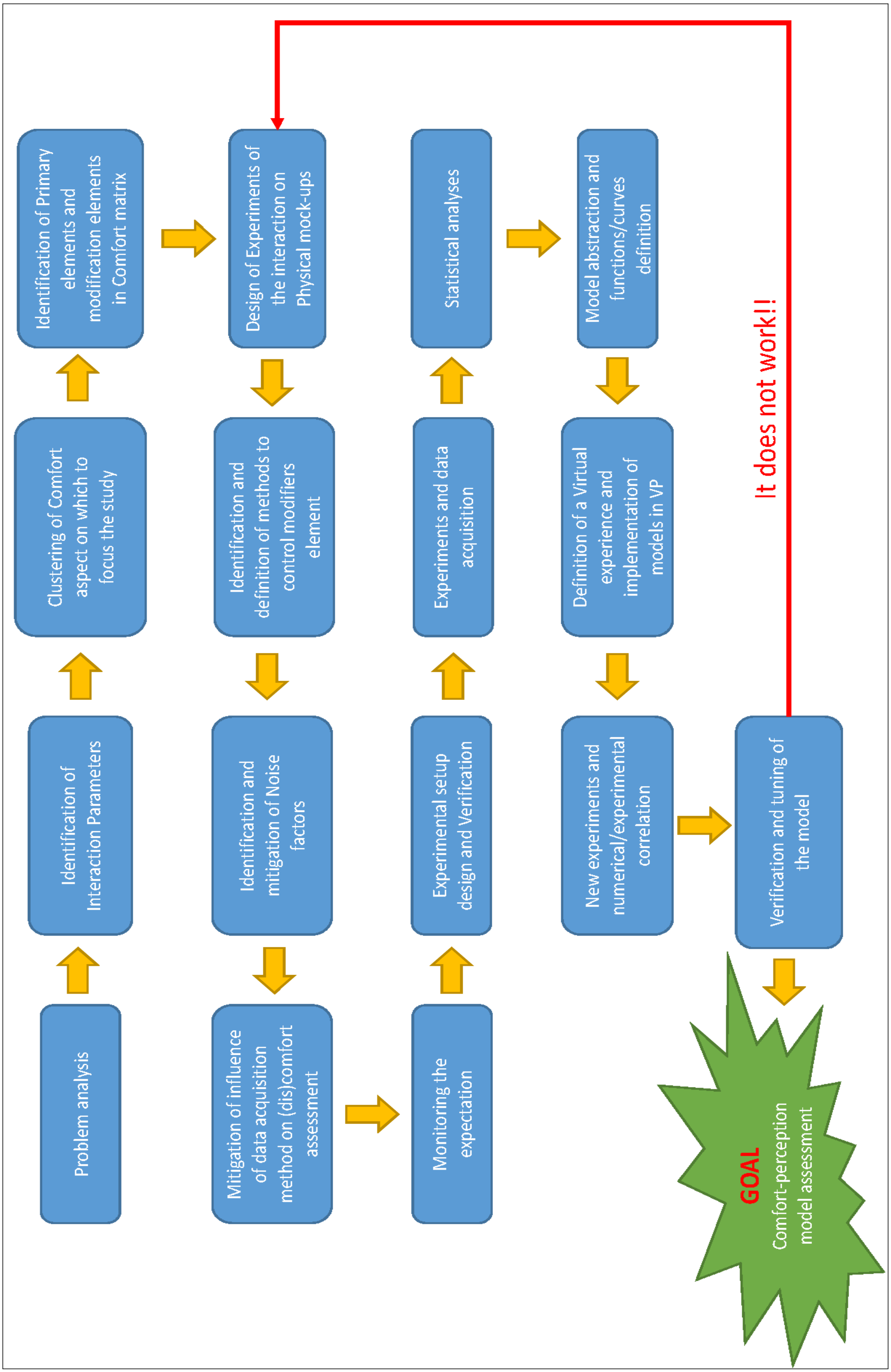

Fig. 9.4: Comfort-related issues: how to perform a good analysis and develop a behavioural model

In this model, the functions that designers have to define are:

1) Direct functions: Functions that describe the links between a primary element and a perception (i.e. anthropometric measures towards perceived postural comfort);
2) Modifier functions: Functions that describe in which way an interaction factor modifies the perception due to a primary one (i.e. the effect of sounds on perceived postural comfort);
3) Weighing/blending functions: functions that describe the weight of the influence of each factor on the global comfort perception (i.e. the cooperative effect of blood vessels' constriction and joint position on perceived postural comfort);
4) Expectation function: the role of the expectation in the global comfort perception.

In Chapters Two and Three, a way to define the Direct functions has been described and applied. It is based on the first part of the path of research represented in the Fig. 9.5.

To achieve a well-working function, the steps defined in Fig. 9.4 must be followed with great attention to the "noise" factors.

The modifier functions can be understood through the conjoint analyses of more factors influencing the same effect in terms of (dis)comfort perception. One limitation of this thesis work is that this aspect of the (dis)comfort equation has not been addressed. A possible way to study this has been explained in the next chapter about future developments.

The weighing/blending functions can be understood through a sensitivity analysis on the influence of interaction factors on the statistical correlations. The method for studying this topic has been investigated in the Chapter Seven but only in a qualitative way. Another limitation of this thesis is that this aspect of the (dis)comfort equation has not been faced using quantitative methods.

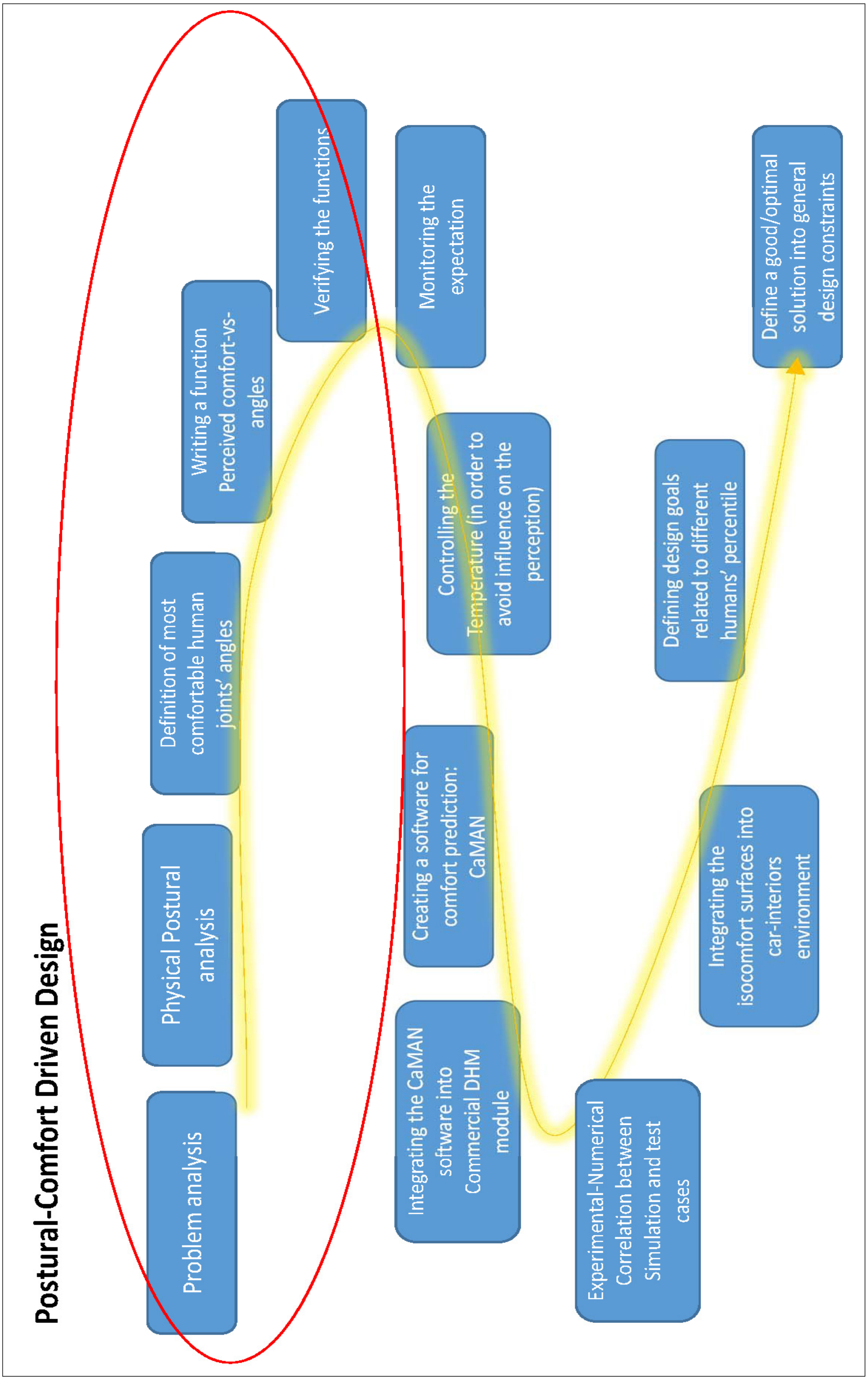

Fig. 9.5: A linear path (in the red ellipse) for defining Direct Functions

Finally, the expectation function have been investigated and described in Chapter Four. It was demonstrated that the use of the placebo effect during experiments allows us to qualify and quantify the expectations influence on the global comfort perception.

9.4 Conclusions

In this PhD thesis answers to the research questions are studied and it is shown that:

- there are laws that allow modelling of the (dis)comfort perception during an interaction. For instance the angle in a joint has an optimum comfort in the neutral position and a low comfort in the extreme position. Another example is that the expectation influences the comfort as well.
- the kind of laws (referring to the question on 'what laws'), discussed in this thesis, can be expressed by writing functions or drawing curves that explain the (dis)comfort perception.
- several methods to more objectively evaluate the (dis)comfort experience of humans are described throughout the thesis, like the CaMAN and the ISO-curves in the car interior design.
- Some guidelines that can be followed as an approach to define functions in the following (dis)comfort equation:

  $$C_i = Mod_C * P_C(h(Pe, Pr, T\&U, We, G\&E) - E$$
  $$D_i = Mod_D * P_D(h(Pe, Pr, T\&U, We, G\&E) + E$$

  are proposed.

  That equation seems to be promising for future developments.

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Chapter 10

Future Developments

10 Future developments

10.1 Imagining the future research

As consequence of the discussion and the conclusion of this thesis, the approaches and methods are deployable and improvable. The work itself shows several limitations, often due to the subjective nature of comfort. Additionally, the recorded comfort perception are dependent on the type of analysis and on the time/duration/costs of the experiments.

Nevertheless, it is possible to underline and outline a study-line to widen the results and to complete (or, if not possible, to improve) the (dis)comfort equations.

Future developments can be assessed during experiments, finding the right balance between the affordance of the experiment itself with the real interaction simulated/experienced and the elimination of all overlapping (among interactions' elements) and interacting effects due, for example, to noise.

The right way to move forward seems to be figuring out experimental setups in which all (previously called) primary elements can be studied in an independent way (in the first attempt) and in a selective interactive way (in the following attempt) by composing the recognized relevant factors in pairs, in groups of three, four and so on, as in [1]. The right theoretical instruments to use are DOE (Design of Experiment) and techniques of analysis such as Montecarlo. It is necessary that enough time and a high investment be provided for designing the right setup. The still the subjective element will play a role, which means that experiments with more subjects under prescribed conditions will be needed with small groups or large groups are needed in free conditions to enlarge the chance of finding relationships.

The use of virtual or mixed reality setup is promising and can help the designers but cannot substitute the reality, as shown in Chapter 5. Also, as comfort is not only influenced by visual information. Tactile information is important too and is hard to model in VR.

Modifier functions have been described as an easy method to understand the weight of a modifier factor on the overall perception. Nevertheless, this aspect has not been assessed by this thesis but is the subject of recent work in progress [2,3], where this method has been applied and some cases have been investigated. The most challenging element is recognizing factors that can affect a perception as a modifier rather than to quantify the effect of them. An easy way to do so is suggested by the AHP (Analytic Hierarchy Process) theory [4]; T. L. Saaty describes an instrument that allows us to codify the knowledge of experts in terms of influence matrices, then use them to recognize the relative influence among all recognized factors to affect a perception. This method could be implemented to achieve better results.

Finally, the blending functions used in the (dis)comfort equation are difficult. A future implementation of this topic might explore analysis and synthesis methodologies for defining a strategy to conduct sensitivity analyses on factors that interact in perception formation. A great effort should be spent on the definition of a quantitative method for conducting these analyses and for extracting some (previously called) weights. The fuzzy theory [5-7] could be helpful in this case. Fuzzy theory allows expression, in a quantitative way, the qualitative knowledge coming from experts or literature [8,9]. The definition of 'membership functions' that describe the complex behaviours (intrinsic in the subjective perceptions) might allow us to develop such methods.

Another great challenge is recognized in understanding the priorities our brain uses for assessing perception and defining it as a comfortable or an uncomfortable experience. The new studies about brain interfaces [10] seem promising in this field.

Summarising, several design methods can be used for (dis)comfort assessment and for its quantification in a quasi-objective way: The challenge is to find the way, time, money, people and energy to develop them.

10.2 General Open issues

From the study of the recent literature, many general open issues can be identified in the topic of quantifying (dis)comfort.

Some have been highlighted in the discussion paragraphs of each chapter and addressed in Conclusions. Nevertheless, other development paths have emerged from this thesis' studies.

In postural comfort fields of research, for example, the mechanical behaviour of the spine and its effect and weight on (dis)comfort evaluation is a rather underdeveloped topic, even though it is an important path to understanding the effect of posture on perceived comfort. This problem is strictly correlated with what happens in the tissues like muscles, ligaments and tendons [11.12]. Knowledge on physiology of the musculoskeletal system, brain behaviour and working of the neurological system apparatus is inevitable in this field [10]. The (dis)comfort perception under low loads is the last frontier of this kind of study.

Another underdeveloped area of research, is the evolution of comfort in time. Even if several studies have been conducted about that subject [3,13-16], it needs deeper investigation. It is difficult due to the long timespan involved for subjects during tests campaigns.

In physiological comfort, one issue is understanding the role of transpiration at the interface between artefacts and the human body parts (and consequent sweating) on the (dis)comfort perception. By now, the main difficulty is in finding the right devices to measure it without affecting comfort itself. Finally, a working model of human skin behaviour must be correlated with the consequent comfort perception. Some studies have been done in this field of research, as reported in the Introduction chapter, but more is needed.

In psychological comfort, deep investigation is required into the effects of expectations [17], pre-conditioning [18] and emotional status [19,20] on comfort/discomfort perception, while in environmental comfort, much work has been done (see Introduction), the same quantity of work has to be done because the elements of the environment in which a human/artefact interaction take place are too numerous.

In a single picture, the future development and the open issues of this thesis can be recognized as the complement to the work made (see Fig. 10.1).

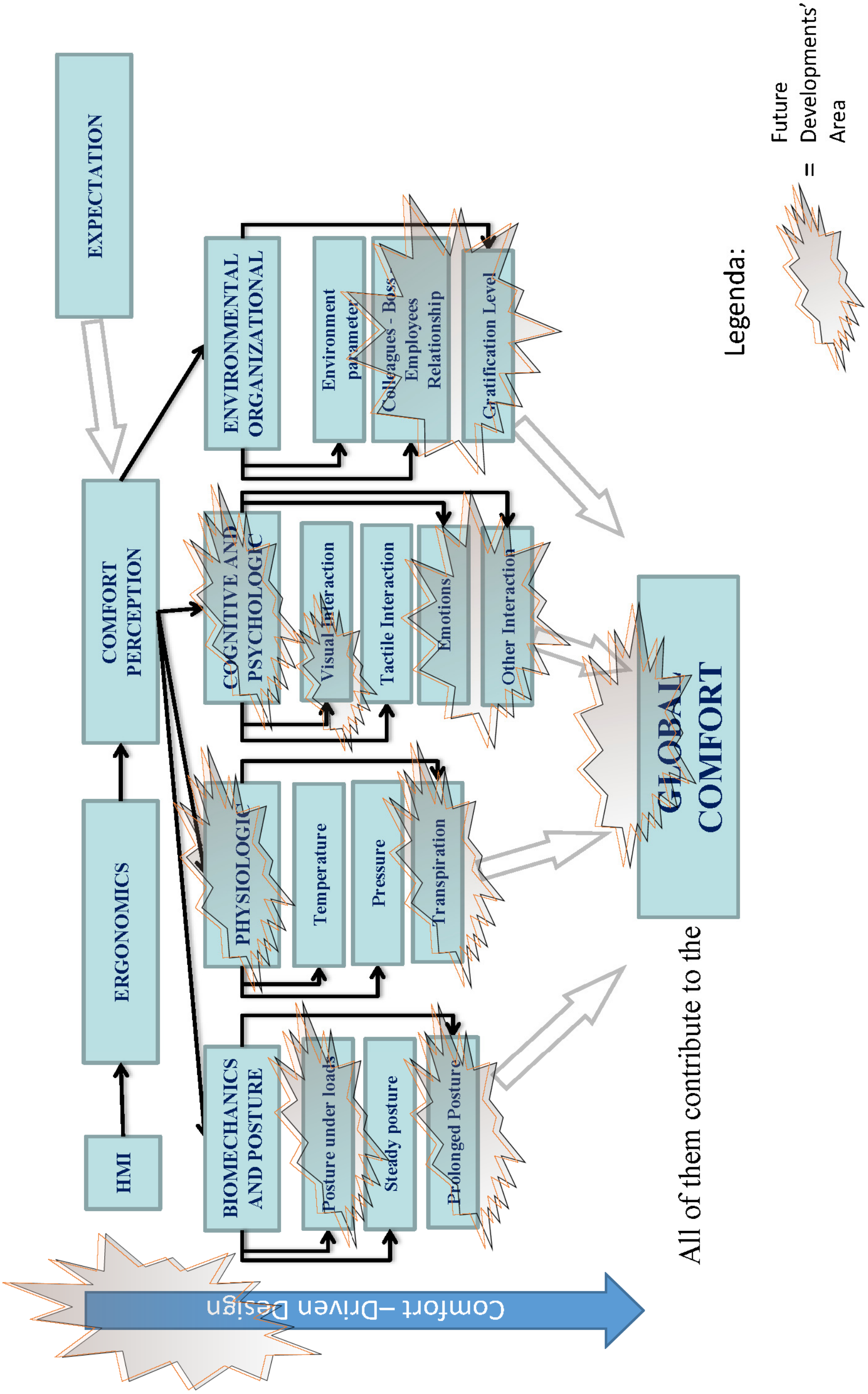

Fig. 10.1: Future Developments

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Summary

Here we are.

About two hundred and fifty pages PhD Thesis to face an Oxymoron that is on the basis of the entire work: “trying to objectify a subjective perception”. In these few words, the author would like to resume all the statements, the research goals and the future perspectives of his work.

The work starts from a societal issue: A comfortable artefact helps people to improve their well-being and can be sold easier. In order to fulfil these two requirements (wellbeing and companies’ profit) a comfort-driven human-centred design method is needed.

But a design method can be developed only if a comfort-model for predicting the comfort perceptions while using artefact can be discovered and/or developed.

In fact, in the Preface, starting from the thoughts of Stephen Hawking that, talking about the unified theory of Physics that might connect General Relativity theory with Quantum Mechanics , in 1998 said “*it may not aid the survival of our species; it may not even affect our life-style. But ever since the down of civilisation, people have not been content to see events as unconnected and inexplicable. They have craved an understanding of the underlying “MAIN ORDER” in the world*”, the purpose of this PhD thesis has been declared: the investigation and the look of a model useful to describe, analyse, evaluate and predict (dis)comfort perceptions.

The contribution of this PhD work to solve this issue can be resumed by the following statement:

“*Starting from the proposal for a general framework for describing comfort perception and a general law for predicting it, some studies about specific comfort performances have been conducted in order to define some comfort “functions” and to propose a design-path that should help designers and companies to improve the comfort performance of new products*”.

In this thesis, methods are developed and theoretical/empirical data were gathered in order to give an answer to the following research questions:

1) Can a comfort driven design method be developed and implemented in the products’ improvement process?

2) If so, what are the laws (νόμος) that allow the modelling of the (dis)comfort perception during an interaction? (Like user or, more generally, like human?)
3) Is it possible to develop a method to more objectively evaluate the (dis)comfort experience of humans?
4) What is the right research approach to define functions in the (dis)comfort equation?

In answering these research questions it appeared that human behaviour remains one of the most difficult notions to explain and, consequently, to model, both in terms of “human body reactions” and in terms of “brain mechanisms of understanding and interpreting body signals”. In the last 15 years it was possible to find five “comprehensive models” that considered many aspect of human perception: Models described by the authors Helander, Moes, Vink-Hallbeck, Naddeo-Cappetti and Vink. The last one states that a general interaction that provokes a feeling of comfort, discomfort or nothing has been named the human-artefact-interaction (HAI); this acronym perfectly describes what happens in everyone’s daily lives.

This was the “Start” point to develop a journey, along the Thesis, that can drive engineers and designers to develop of a general method for understanding and "decoding" human behaviour in terms of (dis)comfort perceptions during a HAI.

In Chapter Two, the range of rest posture (RRP) – a new concept in human postural measurement that has proven of use for comfort evaluation – was introduced and described. The study focused on the identification of the RRP within the comfort range of motion (CROM) for the following human joints: neck, shoulder, elbow, wrist and ankle. 85 humans participated in the study to define the RRP, ROM and CROM. The result was the definition of an easy method using experimental analysis and statistical evaluations identifying RRP in CROM of human joints; by this method, both RRP and maximum level of comfort (MLC) positions have been recognized. These positions were the foundations of the following studies that objectify postural comfort.

In Chapter Three, a new quantitative method for evaluating the upper limbs’ postural comfort (without applied loads) has been developed based on anthropometric parameters and upper limb posture. The main goals of this work were the explanation of an easy method for identifying functions that describe the perceived postural comfort related to the position of each human joint and the consequent development of an easy-to-use tool, named CaMAN®, for evaluating the perceived postural comfort for upper limbs.

Chapter Four presented the results of expectation influence on comfort evaluation. The study allowed to assess that there is an indirect correlation between "expected comfort" and "perceived comfort". In an experiment with 33 participants who both tested an expensive mattress and a cheap mattress, the expensive mattress was experienced as significantly more comfortable, while both mattresses were equal, which shows that expectation has influence on the comfort experience. An increase of the expected comfort implied a decrease of the perceived comfort, and a decrease of the expected comfort implied an increase of the perceived one. As indirect result, it was demonstrated that an increase of the expected comfort implied an increase of the perceived discomfort, and a decrease of the expected comfort implied a decrease of the perceived discomfort.

In Chapter Five, the Kansei technique was used as a comfort-evaluation tool to assess the individual and subjective emotional impressions of a car seat, where all senses of the consumer are involved. In the study various interactions were used: the interaction with the real prototype, presentation of a real prototype, photographic presentation of a real prototype, presentation of a 3D virtual digitized prototype, and interaction with the real prototype placed inside the car. The study demonstrated the power of Kansei method as an easy tool of investigation in cases of emotional evaluation; it also demonstrated how the same object looked different if evaluated using different human-artefact level of interaction. For instance, the highest score of comfort was obtained when the subjects evaluated the seat inside the car, simulating the driving experience. Finally, the effects of external and environmental factors on the perceived comfort have been assessed as very influencing factors.

In Chapter Six, one factor that influences physiological comfort perception has been investigated: the temperature difference between users and the objects with which they interact. A specific temperature measuring system that did not affect the perceived comfort during temperature acquisition has been developed for performing this study. A lack of strong correlations between skin temperature changes and comfort perception changes was found in case of short-time evaluation (15 minutes) and it was assessed that, in general, the increase of temperature variation causes a reduction in comfort.

In Chapter Seven, a study of the combined effects of pressure, posture and load distribution on perceived comfort while seated was described. The specific aim of this study was to further investigate the impact of postural, personal and seat pan interface pressure on comfort factors. The main results of this study were that the pressure distribution and the load distribution are perceived by subjects in different ways: pressure distribution affects perceived physiological and tactile (dis)comfort due to a direct interaction with the "human sensors" belonging to the human skin and to the vessels, while load distribution affects perceived postural and physical (dis)comfort due to its influence on body balance and to the muscle-response of the whole body and, in particular, of the spine.

Chapter Eight presented an example of a comfort-driven target setting and the consequent comfort-driven redesign of a car's dashboard under specific design constraints and targets. The results were a series of iso-comfort curves and surfaces that allowed the controls to be positioned to maximise predicted comfort. An example application on an FCA car was provided.

In Conclusion and Future Developments, finally an answer for each research question has been given.

To the first research question the answer is yes. Several chapters show that a comfort driven design method can be developed. For instance the chapters on the comfortable positions of joints show that close to neutral is preferred, which can be applied in design, which is realized in the chapter where the dashboard is designed. However, further research is needed as most studies in this PhD describe the effect of the elements separately, while in reality a combination is found and the effects of the combinations is largely unknown.

The second research question on the laws that allow the modelling of the (dis)comfort perception can also be partly answered. For instance, the joint study shows that 'neutral' is preferred and the expectation study shows that comfort can be influenced by the pre-comfort phase. However, much work is needed to establish all relevant laws.

The third question on whether it is possible to develop a method to more objectively evaluate the (dis)comfort experience of humans can be answered as no as for individuals this will be hard to predict. But that is not always true. New discoveries about how the body works have allowed us to understand the direct link between some human reactions, like the in this PhD described link between weight distribution and perceived postural comfort. However, also in this field much research will be needed.

On the fourth question on the right research approach to define functions in the (dis)comfort equation the first steps are made and a first equation is presented, which seems worthwhile.

This PhD shows that objectifying comfort is possible to a large extend, which does increase the chance that a product is perceived as comfortable. This is helpful in designing products that contribute to human well-being. However, the final judgement on comfort can not be predicted by 100% certainty as it will always be made by an individual end-user.

Samenvatting

Het is eigenlijk een onmogelijke opgave om in 250 pagina’s te proberen comfort te objectiveren. Comfort is namelijk een ervaring en die kun je niet objectief vast leggen. Toch is de zojuist gepresenteerde eerste zin van de samenvatting een resume van de stellingen en onderzoeksvragen in dit prefschrift en het toekomstperspectief dat in dit proefschrift wordt aangeroerd.

Dit proefschrift beschrijft eerst het maatschappelijk belang: een comfortabel artefact kan bijdragen aan het welzijn van mensen en het beschrijft dat comfort ook commercieel interessant is. Om zowel het welzijn van de gebruiker als de omzet van het bedrijf te vergroten kan een ‘comfort driven’ en ‘human centred’ ontwerp aanpak handig zijn. Een aanzet hiertoe is beschreven in het begin van het proefschrift. Bij het maken van zo een ontwerp aanpak is het ontwikkelen van een comfort model handig, waarmee de comfort perceptie kan worden voorspelt.

In het voorwoord staat een quote van Stephan Hawking: ‘Het zal niet ons dagelijks leven of ons lot veranderen, maar sinds het begin van de beschaving hebben mensen liever niet te maken met onsamenhangende of onverklaarbare verschijnselen. Mensen proberen de grote lijn te begrijpen die onder alle dingen en gebeurtenissen liggen.’ In deze lijn is in dit proefschrift een model gemaakt, waarmee een poging wordt gedaan de comfort perceptie te beschrijven, analyseren, evalueren en te voorspellen. Het startpunt van dit proefschrift is het algemene kader waarin comfort perceptie wordt beschreven. Binnen dit kader zijn een aantal experimenten uitgevoerd waar invloeden op comfort zijn bestudeerd, zodat comfort vergelijkingen kunnen worden opgesteld, zodat ontwerpers beter kunnen voorspellen wat het effect van het product is op comfort.

Dit proefschrift probeert bij te dragen aan de volgende onderzoeksvragen:

1) Kan een comfort gerichte ontwerpmethode ontwikkeld worden en geïmplementeerd worden in het product ontwikkelingsproces?
2) Zo ja, wat zijn de regels die modelleren van de (dis)comfort perceptie (van bijvoorbeeld gebruiker of meer algemeen ‘de mens’) tijdens een interactie mogelijk maken?
3) Is het mogelijk een methode te ontwerpen om meer objectief de (dis)comfort ervaring te evalueren?

4) Wat is de juiste aanpak om een (dis)comfort vergelijking op te stellen?

Bij het beantwoorden van deze vragen blijkt dat het verklaren van het menselijk gedrag een van de lastigste problemen te zijn. Reacties van het menselijk lichaam en hoe het menselijk brein signalen ontvangt en bewerkt zijn moeilijk te modelleren. Er zijn de laatste 15 jaren wel verschillende comfort modellen verschenen in de wetenschappelijke literatuur, bijvoorbeeld van de auteurs Helander, Moes, Vink-Hallbeck, Naddeo-Cappetti and Vink. De laatste auteur stelt dat het de mens-artefact interactie tot een ervaring van comfort, discomfort of geen bewuste comfort ervaring leidt. Dit is een mooie beschrijving van wat er in het dagelijks leven gebeurt en is daarom gekozen als start punt van dit proefschrift om ingenieurs en ontwerpers te helpen om de relatie tussen het artefact en de comfort ervaring te begrijpen.

In hoofdstuk twee is de neutrale stand van gewricht bepaald (=RRP = range of rest posture) en de uitslag die in een gewricht mogelijk is (ROM=range of motion). Dit is bij 85 proefpersonen vastgesteld. Tevens is bepaald waar het comfort maximaal is en dat bleek dicht bij de neutrale stand te zijn. Voor de volgende gewrichten is dit uitgezocht: nek, schouder, elleboog, pols en enkel. Per gewricht is dan bekend in welke standen veel comfort wordt ervaren en welke standen heel weinig. Vaak is het comfort laag in de uiterste standen. Hierdoor is een basis gelegd om comfort te objectiveren.

In het derde hoofdstuk is bij 100 proefpersonen een comfort curve per gewricht gemaakt bij verschillende taken. Dit is in vergelijkingen gezet. De resultaten van de experimenten zijn in een software tool ‘CaMAN’ gezet, die door ontwerpers en engineers gebruikt kan worden bij het ontwerpen van een werkplek, waarbij nagegaan moet worden wat het effect op het comfort van de bovenste ledematen is.

Het vierde hoofdstuk is een experiment waarin het effect van verwachting op comfort is vastgesteld. 33 proefpersonen testen zowel een duur als een goedkoop matras. In feite waren beide matrassen gelijk maar de proefpersonen waren bekend met het prijsverschil. Het dure matras werd als significant meer comfortabel ervaren, wat aantoont dat verwachting het comfort beïnvloed.

In hoofdstuk vijf is Kansei engineering toegepast om de emotionele beleving van een autostoel te onderzoeken. In de studie zijn verschillende vormen van interactie gebruikt: een interactie in het echte prototype, tonen van het prototype op foto, tonen van een 3d VR model en het prototype geplaatst in een auto. Kansei engineering bleek een handige methode te zijn en er zijn verschillen gevonden in de wijze waarop het product werd ervaren. De hoogste comfort score werd gehaald bij het prototype in de auto zelf. Het laagste bij de foto. Dit toont aan dat het ervaren van de omgeving belangrijk is bij de beleving van comfort.

In hoofdstuk zes is een onderzoek gedaan naar het effect van temperatuur op comfort. Een nieuw temperatuurmeetsysteem tussen lichaam en matras was ontwikkeld, die niet gevoegd wordt. Er waren echter geen duidelijke correlaties gevonden tussen temperatuur en comfort. Wel was duidelijk dat sterke temperatuurschommeling omhoog een lager comfort tot gevolg had.

In hoofdstuk zeven is een combinatie van druk tussen stoel en zitting, houding en verdeling van het gewicht onderzocht in relatie tot comfort. Interessant was dat drukverdeling is gerelateerd aan het ervaren fysiologische en tactiele (dis)comfort. Wellicht omdat de sensors in de huid en vaten dit waarnemen. Lichaamsgewicht verdeling was gerelateerd aan houdings(dis)comfort en fysiologisch (dis)comfort. Wellicht omdat hier de spierreactie in het totale lichaam en rond de wervelkolom een belangrijker rol speelt.

In hoofdstuk acht wordt een demonstratie gegeven over hoe kennis in software ingebouwd kan worden dat gebruikt kan worden door ontwerpers en ingenieurs. Een voorbeeld van een dashboard ontwerp is gegeven, wat met de software geoptimaliseerd kan worden door de comfortabele reikwijdtes te hanteren, die geprogrammeerd waren in de software.

In de laatste hoofdstukken van het proefschrift wordt gepoogd een antwoord op de onderzoeksvragen te geven.

Het antwoord op de eerste onderzoeksvraag is: ja. Een comfort gerichte ontwerpmethode kan ontwikkeld worden. De hoofdstukken over de comfortabele posities van gewrichten tonen bijvoorbeeld aan dat er een optimale stand is die het meeste comfort geeft wat gebruikt kan worden in ontwerpen. In het hoofdstuk over het dashboard ontwerp is zelfs aangetoond dat deze kennis in ontwerpen gebruikt kan worden. De studies in dit proefschrift betreffen meestal maar één factor die comfort beïnvloed, bijvoorbeeld verwachting of stand van het gewricht. In werkelijkheid gaat het om een combinatie van factoren en meer onderzoek is nodig hoe de combinatie van factoren het comfort beïnvloeden.

De tweede onderzoeksvraag gaat over regels die modelleren van de (dis)comfort perceptie tijdens een interactie mogelijk maken. En dat blijkt gedeeltelijk te kunnen. Ook nu geven de studies over de ideale gewrichtstand aan dat het kan. ‘de stand dicht bij neutraal blijkt meer comfortabel te zijn. Ook uit het hoofdstuk over de verwachting blijkt dat comfort beïnvloed kan worden door de precomfort fase. Dit proefschrift is echter maar het begin van kennisopbouw. Er is nogal wat studie nodig om de regels te kunnen definiëren.

De derde onderzoeksvraag of het mogelijk is om meer objectief de comfort perceptie vast te stellen moet met nee beantwoord worden. Het individuele menselijk gedrag is niet exact te voorspellen. Er komt wel meer kennis waardoor de voorspelling dichter bij de werkelijkheid kan komen op groepsniveau. In dit proefschrift bleek bijvoorbeeld dat gewichtsverdeling meer gerelateerd is aan houdingscomfort. Maar ook hier zal meer onderzoek nodig zijn om de voorspelling beter te maken.

Voor de vierde onderzoeksvraag over het maken van vergelijking zijn de eerste stappen gezet en een vergelijking is opgesteld. Meer onderbouwing voor de verschillende elementen is nodig en ook validatie is uiteindelijk nodig.

Concluderend, geeft dit proefschrift aan dat objectivering van comfort perceptie tot op zekere hoogte mogelijk is, waardoor een product comfortabel gemaakt kan worden. Dat is van belang bij het ontwerpen van producten, die dan kunnen bijdragen aan het welzijn van de eindgebruiker. Maar voorspellen met 100% zekerheid zal nooit lukken omdat uiteindelijk een individuele eindgebruiker bepaalt of iets wel of niet comfortabel is.

About the author

He was born in Salerno (Italy) in 1975.

He had the Master Degree at University of Salerno in Mechanical Engineering, “summa cum laude”, on 1999. He won a scholarship grant by Italian Society of Automotive Engineering (ATA - Associazione Tecnica dell’Automobile – Turin) for his theoretical/experimental MD thesis at ELASIS - FIAT research system in South of Italy.

Since December 1999, he was research collaborator at Dept. of Mechanical Engineering of University of Salerno, in Industrial Design team.

In 2000, he won a scholarship offered as a prize by Dept. of Informatics and Applied Mathematics of University of Salerno on the research topic “Optimization in mechanical design with paracomplete logics”.

From October 2001 to November 2002, he was employed in ELASIS S.c.p.A. (FIAT research system in South of Italy) of FIAT industries, in Product Development Methods team, working as ComputerAidedDesign Specialist on Vehicles Design, Crashworthiness, Pedestrian Tests, Non-metallic Materials Characterization and Software Independence.

While employed in FIAT, he worked:

- in Delft (The Netherlands) at TNO Automotive on February 2002
- in Detroit (U.S.A.) at FIAT R&D on March 2002
- in Ispra (Italy) at JRC (Joint Research Centre) of European Community on September 2002
- in Heidelberg (Germany) at ESI GmbH on October 2001

On October 2002, he won the competitive state exam to become Assistant Professor of Italian S.S.D. ING-ING/15 (Scientific-Disciplinary-Sector of Design and Methods of Industrial Engineering) and on December 2002, he was employed at Engineering Faculty of University of Salerno (the youngest Italian Professor in S.S.D. ING/IND-15).

Since January 2011, he was employed as Aggregate Professor (Assistant Professor with more than 120 hours of teaching activities) at Industrial Engineering Department of University of Salerno with teaching assignments (an average of 150 hours per year) at Faculty of Engineering of University of Salerno in BD, MD and PhD courses of Mechanical engineering, Management Engineering, Chemical Engineering, Architecture and Civil Engineering Departments.

On March 2017, he won the competitive state exam to become Associate Professor of Italian S.S.D. ING-ING/15 (Scientific-Disciplinary-Sector of Design and Methods of Industrial Engineering).

Since 2011 he was member of the National Committee of the University Ministry for the evaluation of Research Projects and for the evaluation of Universities’ “Research products” (papers, publications, patents, books, ...).

Since 2007, he was responsible for the Virtual Reality Lab. of University of Salerno.

He was Visiting Professor at Dumlupinar University in Kutahya (Turkey) in 2014,

at Transilvania University in Brasov (Romania) in 2015, at Delft University of Technology in Delft (The Netherlands) two times in 2016, at Politehnica University of Bucharest (Romania) in 2016.

He was supervisor (promotor) of more than 70 BD and MD Thesis in Mechanical, Management and Civil engineering. He was supervisor and tutor of 4 Joint Master Degree Thesis, in cooperation with La Plata Industrial Engineering (Argentina).

He was promotor of 4 PhD Thesis in Mechanical and Industrial Engineering.

From 2003 to 2011, he was member of the Board for Doctorates in Mechanical Engineering of University of Salerno.

Since 2011, he was member of the Board for Doctorates in Industrial Engineering of University of Salerno.

In last five years, he was part of research teams (as senior researcher or as coordinator/scientific manager) in 18 national/international research projects for an overall funding value of about 6.2M€.

He works on research topics about Virtual Prototyping and Innovative Design Methods development. His studies deal with Industrial Design Methods and techniques, Design Theory, Design Optimization, Computer Aided applications development. Developed theories and methods have been applied in Automotive industries, in Aerospace companies, in Product/process design and optimization, in Human health and safety, in Biomedical engineering.

On these topics, he published some books' chapters and more than 80 paper in International Conferences, International Journals and book series.

He is member of the USA-chapter of SAE (Society of Automotive Engineerig), member of Europe chapter of HFES (The Human Factors and Ergonomics Society), senior member of the ADM-INGEGRAF International Design Association and former member of ISGG (International Society for Geometry and Graphics).

List of publications

1. *Apostolico, A., Cappetti, N., D'Oria, C., Naddeo, A., Sestri, M. (2014). Postural comfort evaluation: experimental identification of Range of Rest Posture for human articular joints. International Journal on Interactive Design and Manufacturing (IJIDeM), 8, 109-120.*

2. *Naddeo, A., Cappetti, N., Vallone, M., Califano, R. (2014). New trend line of research about comfort evaluation: proposal of a framework for weighing and evaluating contributes coming from cognitive, postural and physiologic comfort perceptions. In Proceedings of the 5th International Conference on Applied Human Factors and Ergonomics AHFE, edited by T. Ahram, W. Karwowski and T. Marek.*

3. *Naddeo, A., Cappetti, N., D'Oria, C. (2015). Proposal of a new quantitative method for postural comfort evaluation. International Journal of Industrial Ergonomics, 48,25-35.*

4. *Naddeo, A., Cappetti, N., Vallone, M., Califano, R. (2015). The role of expectation in comfort perception: The mattresses' evaluation experience. In Proceedings of the 6th International Conference on Applied Human Factors and Ergonomics AHFE, 26-30 of July 2015, Las Vegas (USA).*

5. *Naddeo, A., Apicella, M., Galluzzi, D. (2015). Comfort-Driven Design of Car Interiors: A Method to Trace Iso-Comfort Surfaces for Positioning the Dashboard Commands. SAE Technical Papers.*

6. *Naddeo, A., Califano, R., Cappetti, N., Vallone, M. (2016). The effect of external and environmental factors on perceived comfort: the car-seat experience, In D. de Waard, K.A. Brookhuis, A. Toffetti, A. Stuiver, C. Weikert, D. Coelho, D. Manzey, A.B. Ünal, S. Röttger, and N. Merat (Eds.). Proceedings of the Human Factors and Ergonomics Society Europe Chapter 2015 Annual Conference (pp. 291-308).*

7. *Califano, R., Naddeo, A., Vink, P. (2017). The effect of human-mattress interface's temperature on perceived thermal comfort. Applied Ergonomics, 58, pp. 334-341. doi: 10.1016/j.apergo.2016.07.012*

8. *Naddeo A. (2017). Comfort-driven target setting. Plenary speech, in proceedings of the 1st International Comfort Congress, Salerno (Italy), June 7th and 8th, 2017 Edited by Alessandro Naddeo. ISBN: 979-12-200-2249-1*

9. *Naddeo, A., Califano, R., Vink, P. (2017). The effect of posture, pressure and load distribution on perceived (dis)comfort. Analysis of a school chair with rigid seat and without armrests. Submitted to Ergonomics in 2017.*

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