UNIVERSIDAD POLITÉCNICA DE MADRID
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**DESIGN, CHARACTERISATION AND
APPLICATION OF MULTIMODAL HAPTIC
INTERACTION SYSTEMS FOR THE TORSO IN
VIRTUAL ENVIRONMENTS**

DOCTOR OF PHILOSOPHY
AUTOMATION AND ROBOTICS

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ELECTRÓNICA E INFORMÁTICA INDUSTRIAL
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Resumen

En cualquier situación cotidiana, el sentido del tacto es fundamental para interactuar con todo aquello que nos rodea, pues proporciona diversa información del entorno y de los objetos, como la textura, el peso, el estado (sólido, viscoso) o la temperatura, que no se puede percibir a través del resto de sentidos. Actualmente, al simular una situación real en un entorno virtual, usualmente se emiten estímulos visuales y auditivos, que son los más sencillos de reproducir. Sin embargo, el sentido del tacto se mantiene infrautilizado, perdiendo toda esa información que podría contribuir a desarrollar una sensación completa de experimentar una situación real. En los últimos años, la inclusión de dispositivos hápticos en sistemas de realidad virtual se ha incrementado exponencialmente, pero centrándose en aquellas zonas del cuerpo que permiten interactuar de manera activa con el escenario virtual (por ejemplo, las manos), olvidando las zonas de cuerpo que pueden estimularse de manera pasiva, como el torso.

En esta tesis, se presenta el diseño y el desarrollo de un chaleco háptico para el torso que incluye realimentación vibrotáctil, térmica y de impacto. Los actuadores vibrotáctiles son motores de masa excéntrica rotatoria, que proporcionan un amplio rango de vibraciones para crear patrones hápticos. En este caso, los motores se han caracterizado para optimizar su funcionamiento de acuerdo a las condiciones experimentales del chaleco háptico. Los actuadores térmicos son células Peltier, que permiten generar estímulos de frío y calor con un solo dispositivo. Por último, dada la escasez de sistemas que simulen impactos, se ha diseñado y desarrollado un nuevo actuador basado en un sistema mecánico que genere impactos fácilmente perceptibles. El último paso ha sido el diseño de los sistemas de control, tanto individuales para cada actuador, como general para controlar el chaleco háptico completo y comunicarse con los sistemas de realidad virtual. También es esencial el diseño textil del chaleco para colocar los actuadores de manera que el dispositivo final no sea pesado ni voluminoso, y para que los actuadores permanezcan siempre pegados a la piel del usuario para transmitir la información háptica de manera fiable.

Tanto la distribución de actuadores en el chaleco como la creación de patrones que proporcionen información precisa a los usuarios deben basarse en variables psicofísicas de percepción sobre el torso, como la agudeza espacial vibrotáctil y térmica permite conocer la distancia que debe haber entre dos actuadores funcionando simultáneamente para que los usuarios perciban dos estímulos distintos. Distribuir los actuadores de acuerdo a esas distancias confiere más versatilidad al proceso creativo, y los patrones hápticos resultantes pueden crear una estimulación generalizada o secuencias que proporcionen información más concreta. Por otra parte, los umbrales perceptivos (absolutos y diferenciales) permiten saber cuáles son los límites para detectar vibraciones o estímulos térmicos, de manera que los patrones creados siempre sean perceptibles y transmitan la información de manera fiable.

Una vez diseñado y desarrollado el chaleco, se ha validado para asegurar que la configuración es correcta y que la creación de patrones vibrotáctiles, térmicos y de impacto es fiable.

La validación consistió en crear estímulos en todas las zonas del torso, que los usuarios debían identificar y detallar sus características. Como los resultados fueron satisfactorios, el chaleco háptico está preparado para integrarse en un sistema de realidad virtual.

El siguiente paso fue realizar pruebas para comprobar si el chaleco se integra correctamente en sistemas de realidad virtual y si proporciona beneficios a los usuarios. En el primer experimento, el usuario tenía que interaccionar con un entorno virtual en el que se produce una explosión. Los resultados determinaron que el chaleco háptico mejora la inmersión en el entorno virtual y, por lo tanto, proporciona beneficios para finalizar las tareas encomendadas con más facilidad y seguridad. Además, el experimento también indicó que la percepción varía en función de la experiencia previa de los usuarios con sistemas similares. Los usuarios profesionales evaluaron de forma más crítica que aquellos usuarios que nunca habían utilizado sistemas de realidad virtual o dispositivos hápticos.

La validación y el primer experimento mostraron acciones correctivas para mejorar el funcionamiento del chaleco háptico. En el siguiente experimento se utilizó el chaleco háptico optimizado integrado en un entorno virtual para potenciar las características estresantes o angustiosas, buscando potenciar las respuestas de los usuarios respecto a la inmersión y el sentido de presencia percibidos. En este caso, se añadieron evaluaciones objetivas (medidas fisiológicas u observación de las respuestas autónomas, entre otras) para reforzar los resultados subjetivos. No solo se mejoraba la percepción subjetiva respecto a la prueba anterior, sino que las medidas objetivas respaldaron firmemente las conclusiones sobre la influencia del chaleco háptico en cuando al incremento de la inmersión y la presencia en el entorno virtual, así como en la optimización del rendimiento de los usuarios para completar las tareas encomendadas.

Finalmente, la colaboración con el Perceptual Robotics Laboratory (PERCRO) de la Scuola Superiore Sant'Anna - TeCIP Institute de Pisa, permitió avanzar hacia el desarrollo de dispositivos hápticos de cuerpo completo, integrando un dispositivo para la punta del dedo que permitía interactuar activamente con el mismo entorno virtual estresante. La integración conjunta de ambos elementos (el chaleco y el dispositivo manual) otorga mayor versatilidad para interaccionar con el escenario virtual, optimizando las sensaciones de los usuarios y el rendimiento para completar las tareas y cumplir los objetivos. Los resultados de este experimento ayudan a establecer las bases para la creación de dispositivos hápticos completos que consigan que un usuario perciba un entorno virtual a través de cualquier parte del cuerpo como si estuviera en una situación real.

Abstract

The sense of touch is fundamental to interact with the surroundings in whichever daily situation since it provides diverse information of the environment and the objects, such as textures, weight, state (solid, viscous) or the temperature, that a human being cannot perceive through the rest of the senses. Currently, the simulation of a real situation in a virtual environment usually renders visual and auditory stimuli because they are simpler to create. However, the sense of touch remains underused, losing all that information that would contribute to develop the full sensation of being experiencing a real situation. During the last years, the inclusion of haptic devices in virtual reality systems have increased exponentially, but focusing on those areas of the body which allow an active interaction with the virtual scenario (e.g. the hands), forgetting those areas which can be passively stimulated (e.g. the torso or the legs).

In this thesis, I designed and developed a haptic vest for the torso, which contains vibrotactile, thermal, and impact feedback. Vibrotactile actuators are eccentric rotating mass motors, which provide a broad range of vibrations intensity to create haptic patterns. In this case, the motors have been characterised to optimise their operation according to the experimental conditions of the haptic vest. The thermal actuators are Peltier cells, which allow the rendering of cold and hot stimuli with a single device. Lastly, I designed and developed a new actuator owing to the scarcity of systems for simulating impacts. The actuator is based on a mechanical system to render impacts readily perceptible. The last step was the design of the control systems for each actuator, and an overall control system to handle the entire haptic vest and communicate with virtual reality systems. It is also essential the textile design of the vest to place the actuators so that the definitive device is not heavy or bulky, and actuators remain always fully attached to the user's skin for conveying the haptic information dependably.

Both the distribution of actuators in the vest and the creation of haptic patterns which provide accurate information to users must be based on psychophysical variables of the perception over the torso, such as the vibrotactile and thermal spatial acuity afford to know the required distance between two actuators simultaneously operating so that users perceive two different stimuli. Distributing the actuators according to those distances confers more versatility to the creative procedure, and the ensuing haptic patterns can serve either to create a generalised stimulation or to develop haptic sequences to provide more specific information. Furthermore, the perceptual thresholds (absolute and differential) afford to know the limits to detect vibratory or thermal stimuli, in such a manner that created patterns are always perceptible, and they convey accurate information.

It was necessary to validate the design and the development of the vest to ensure that the configuration is adequate, and the creation of vibrotactile, thermal, and impact patterns is reliable. The validation experiment consisted of creating stimuli all over the torso, which users had to identify and detail all their characteristics. As results were satisfactory, the

haptic vest is ready for its integration into whichever virtual reality system.

The next step was to conduct several tests to verify if the haptic vest is integrated appropriately into virtual reality systems and if it benefits the user's experience. In the first experiment, the user had to interact with a virtual environment during a post-explosion scenario. Results determine that the haptic vest improves the subjective perception of the virtual environment (immersion and sense of presence) and, therefore, it provides benefits to end the entrusted tasks with more easiness and accuracy. Moreover, this experiment also denoted that the perception differs according to the previous expertise of users with similar systems. Professional users customarily assessed more critically than those users who had never employed virtual reality systems or haptic devices.

The validation and the first experiment revealed corrective actions to enhance the operation of the haptic vest. The next experiment employed the optimised vest integrated into a stressful and distressing virtual environment, aiming to foster the user's responses regarding the immersion and the sense of presence. Moreover, this experiment also employed objective measures (physiological constants or the observation of autonomous physical responses, among others) to reinforce the subjective results. Not only did the subjective perception improve regarding the previous experiment, but the objective measures firmly bolstered conclusions about the influence of the haptic vest for increasing the immersion and the sense of presence in the virtual environment, and optimising the performance to complete the entrusted tasks.

Finally, the collaboration with the Perce Perceptual Robotics Laboratory (PERCRO) de la Scuola Superiore Sant'Anna - TeCIP Institute in Pisa afforded to move forward the development of full-body haptic devices, integrating a fingertip haptic device to interact actively with the same stressful virtual environment. The joint integration of both elements (i.e. the fingertip device and the haptic vest) gives more versatility to interact with a virtual scenario, optimising the user's sensations during the experience and the performance to finish the tasks and fulfil the objectives. Results of this experiment support to set the foundation for creating full-body haptic devices so that users accomplish the perception of a virtual environment through whichever body part as if they were in a real situation.

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Publications

Main Publications

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G. García-Valle, S. Arranz-Paraíso, I. Serrano-Pedraza, M. Ferre. *Estimation of the Torso Vibrotactile Thresholds using Eccentric Rotating Mass Motors*. Transactions on Haptics. To be published.

G. García-Valle, M. Ferre, J. Breñosa, R. Aracil, J.M. Sebastián and C. Giachritsis. *Design and Development of a Multimodal Vest for Virtual Immersion and Guidance*. International Conference on Human Haptic Sensing and Touch Enabled Computer Applications, pp. 251-262, July, 2016. Springer, Cham.

Secondary Publications

D.V. Frutos, G. García-Valle, J. Breñosa, J.B. Carrión and M. Ferre. *Chaleco Háptico Multimodal para Aplicaciones de Realidad Virtual*. Jornadas de Automática, 2017.

G. García-Valle, J.C. Ramos, J. Breñosa and M. Ferre. *Analysis of Haptic Resolution on Torso for Thermal and Vibrotactile Actuators in a Virtual Reality Vest*. RoboCity 2030, May, 2016.

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G. García-Valle, J. Breñosa and M. Ferre. *Haptic Vest for Multimodal Immersion in Virtual Environments*. WorldHaptics 2017, Munich, Germany.

G. García-Valle, J. Breñosa and M. Ferre. *Haptic Vest for Multimodal Immersion in Virtual Environments*. EuroHaptics 2018, Pisa, Italy.

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Acronyms and Abbreviations

2S	2-Stimulus Pattern
2iFC	Two-interval Forced-Choice
3cI	3 consecutive Impacts
3D	Three Dimensional
3NcI	3 Non-consecutive Impacts
3S	3-Stimulus Pattern
4S	4-Stimulus Pattern
5S	5-Stimulus Pattern
7S	7-Stimulus Pattern
AA	Apperance Area
AB	Arduino-Based
AIP	Ascending Intensity Pattern
ANG	ANGular shape of pattern
AR	Avatar block of the Realism questionnaire
AT	Attention block of the subjective questionnaire in Experiment 3
ATh	Absolute Threshold
AV	Absolute Variation
BPM	Beats Per Minute
CB	Central Back
CI	Code Insertion
CR	Comparison with Reality block of the realism questionnaire
CoR	Code Room
CRC	CiRCular shape of pattern
CS	Configuration block of the Subjective questionnaire in Experiment 3
DBE-Phx	Difference of a psychophysical response between the Beginning and the End of the 'x' Phase
DC	DisComfort block of the questionnaire in Experiment 4
DIP	Descending Intensity Pattern
DMM-Phx	Difference of a psychophysical response between the Minimum and Maximum Value of the 'x' Phase
DoS	Duration of each Stimulus
EAR	Environmental Avatar block of the Realism questionnaire
EE-Ph	Variation of a psychophysical response after Events between two phases
EMB	Embodiment block of the subjective questionnaire in Experiment 3
EMS	Electrical Muscle Stimulation

ERM	Eccentric Rotating Mass
FA	Fast Adapting
GM	Global Mean
GR	General block of the Realism questionnaire in Experiment 3
GSR	Galvanic Skin Response
GU	General Users
H	Haptic condition
H2	Second Haptic condition
HAP	HAPtic block of the subjective questionnaire in Experiment 3
HE	Haptic Experts
HF	Haptic Feedback block of the questionnaire in Experiment 4
HMD	Head-Mounted Display
HMI	Human-Machine Interaction
HR	Heart Rate
HRV	Heart Rate Variability
Hs	Haptic condition (subjective questionnaire)
ID	IDentification number
IDE	Integrative Development Environment
INT	Interactivity block of the subjective questionnaire in Experiment 3
ITQ	Immersive Tendencies Questionnaire
IQR	Interquartile Range
KVal	K-Value
LA	Left Abdomen
LB	Lower Back
LIN	Linear shape of pattern
LL	Left Lateral
LLB	Lower Left Back
LLF	Lower Left Front
LM	Leap Motion
LRA	LINear Resonant Actuator
LRB	Lower Right Back
LRF	Lower Right Front
LS	Left Shoulder
M1	Motor 1 - vibrotactile spatial acuity
M2	Motor 2 - vibrotactile spatial acuity
MB	Microcontroller-Based
MFP	Mean of the Final Phase
MIP	Maximum Intensity Pattern

MLB	Medium Left Back
MLF	Medium Left Front
MPP	Mean of the Previous Phase
M-Phx	Mean of a psychophysical response of the 'x' Phase
MR	Multimodality block of the Realism questionnaire
MRB	Medium Right Back
MRF	Medium Right Front
MS	Multimodality block of the Subjective questionnaire
NE	Non-Experts
NEP	Narrative & Emotional Presence block of the subjective questionnaire in Experiment 3
NH	Non-Haptic condition
NHs	Non-Haptic condition (subjective questionnaire)
NoV	Number of Vibrations
NP	Non-Perceived
PCM	Phase-Change Material
PE	Presence & Embodiment block of the questionnaire in Experiment 4
PEx	Previous Expertise block of the subjective questionnaire in Experiment 3
PID	Proportional, Integrative, Derivative
PoV	Point of View
PQ	Presence Questionnaire
PU	Professional Users
PWM	Pulse-Width Modulation
RA	Right Abdomen
RIP	Random Intensity Pattern
RL	Right Lateral
RS	Right Shoulder
SA	Slow Adapting
SB	Search Bomb
SC	Skin Conductance
SCV	Skin Conductance Variability
SD	Standard Deviation
SEM	Standard Error of Mean
SI	Single Impact
SoP	Shape of Patterns
SR	Sound block of the Realism questionnaire
T	Condition according to the order of realisation
TA	Thermal spatial Acuity

TE	Technological Experts
TF	Technical Failures
Ts	Condition according to the order of realisation (subjective questionnaire)
TS	Task-Specific block of the questionnaire in Experiment 4
ULB	Upper Left Back
ULF	Upper Left Front
URB	Upper Right Back
URF	Upper Right Front
VE	Virtual Environment
ViI	Variations in Intensity
VR	Virtual Reality

Chapter 1

Introduction

1.1 Overview

In the last decades, the advent of astonishing technologies and devices has allowed interacting with remote or Virtual Environments (VE) in unsuspected manners thus far. Practically everyone already knows the most typical devices to visualise VEs, whose demanding aim is to make users believe that scenarios are real and vivid situations. However, the communication between humans and machines is often limited to the stimulation of the senses of sight and hear, even when those stimuli are quite akin to the sensations that users ordinarily perceive in daily situations.

Lately, there are more and more systems which contain haptic devices to stimulate the sense of touch, providing experiences even closer to real sensations. Most of these devices primarily focus on stimulating the fingers, hands, or arms, since they are the primary means to interact with real environments. Nevertheless, the rest of the body (torso, legs, or even head) must not be underrated since it is also essential to perceive the surroundings. The lack of haptic devices for those areas is the foundation of this dissertation, which exposes the creation of a haptic vest to stimulate the entire torso (front, back, and shoulders), and accomplish more accurate and realistic feedback in VEs.

The emergence and innovative developments of haptic devices are linked initially to telerobotics. At the outset, the objective was that workers directing a robot in remote environments could feel the same sensations that if they were manipulating the objects with their own bare hands [1] [2]. Since then, these Human-Machine Interaction (HMI) systems have been used continuously for diverse applications such as remote manipulation, spatial awareness systems, or guiding blind people, among others [3] [4] [5].

The rise of Virtual Reality (VR) evolved that original view, and haptic technology permuted to become an essential part of VR systems nowadays. As mentioned before, haptic technology is part of plentiful innovative devices, but perhaps the more outstanding growth has come from its integration into VR systems owing to their technological and economic

potential. As a constituent of those systems, a haptic device can create indications or cues to guide a person in an unknown environment or indicate the presence of certain elements. Thereby, they might serve to enhance the realism of the system or the immersion of users in VEs by creating realistic stimuli akin to real sensations.

If the haptic vest seeks to enhance a VR system substantially, both the design and the development require a thorough analysis to study and determine the main features of the vest to be helpful and fulfil all the requisites. The first step is to decide the kinds of stimulation that the device has to render, then select the specific actuators and, finally, configure and synchronise all systems to create appropriate stimuli over the users' skin. In this case, the haptic vest includes vibrotactile, thermal, and impact stimulation, but it is essential to know how every one of those stimuli affects the skin in the torso in order to generate the desired sensations.

Therefore, the study of haptic perception in the torso is crucial. The skin has a considerable quantity of receptors connected to the brain, setting up the somatosensory system. These receptors activate when something or someone applies a tactile, mechanical, or thermal stimulus over the skin. The best design of a haptic vest must consider the mechanisms of perception in all areas of the torso. Not only does the study of perception allow ascertaining the best configuration of haptic actuators, but it also avoids that stimuli unleash painful or uneasy sensations, or even damage the body tissues due to unrestrained mechanical or thermal stimuli. Moreover, it also serves to ascertain the minimum thresholds of each feedback to ensure the perception or the differential thresholds to discriminate two consecutive stimuli.

Once the parameters of perception are defined completely, the haptic vest is configured aiming to all actuation systems operate accurately and coordinately. The design needs a validation experiment to verify if the vest works as expected, ascertaining if the actuation systems convey the intended information to users. The validation consists of rendering simple haptic patterns (vibrotactile, thermal, or impact) over different areas of the torso, and responses reveal if users understand the information that the vest intends to transmit. If so, the haptic device is ready to integrate into a VR system.

After that, the haptic vest is integrated into a VR system, aiming that users perceive visual, auditory, and haptic feedback simultaneously. The subsequent experiments become more complicated to ascertain if the haptic vest is helpful to enhance the realism, the immersion or the sense of presence in VEs. In those experiments, participants are deployed in a virtual scenario wearing a Head-Mounted Display (HMD), headphones and the haptic vest. They have to complete specific tasks while interacting with elements in the scenario and, once they finish those tasks, they respond questionnaires to assess the experience. The questions gather the feelings, perceptions, and thoughts of users, but focusing on the influence of the haptic feedback on the whole experiment.

The experiments have significant dissimilarities between them. In the first one, participants are divided into groups according to their expertise with similar systems. They have to complete a primary task, besides exploring and moving around the scenario. They then respond to a subjective questionnaire to assess their experience, the realism of the VR system, and their subjective perception throughout its stay in the virtual scenario.

The second experiment increases the complexity since participants have to counteract a terrorist attack, subduing the assailants and protecting the civilian people. They respond to a new subjective questionnaire after finishing the experiment, assessing the immersion and the sense of presence more thoroughly. Furthermore, the participant's condition is monitored to obtain objective information, gathering data that must be exhaustively examined to attain conclusions about the users' experience and the influence of the haptic vest.

The questionnaires assess the virtual experience, but they ordinarily do not consider the influence of haptic feedback. A haptic vest can strongly affect the users' condition in the VE, changing how they think and perceive while exploring the scenario. Hence, it is necessary to create a questionnaire which includes questions to evaluate how the haptic feedback modifies the perception of VEs. This new survey must also draw from previous questionnaires, suiting the questions to standard features of current VR systems.

The haptic vest may considerably affect a virtual experience despite users only receive information through passive stimuli that tend to be tough to understand. Contrarily, active haptic devices render more intuitive stimuli; thus, they might be helpful to reinforce the information conveyed by the haptic vest. The last experiment proposes an extension of haptic feedback to the hands (i.e. an active body surface). The experiment is similar since participants have to perform specific tasks in the same VE. Likewise, the assessment maintains two standpoints, both the subjective (questionnaires) and the objective (users' condition monitoring), to compare all results afterwards.

The analysis of all results provides a dependable and realistic view about the usefulness of haptics in VR systems, even though they markedly focus on the influence of a single device such as the haptic vest. The objective is to ascertain if a haptic device (i.e. the haptic vest) provides meaningful information to users throughout a virtual experience, enhancing all initially proposed aspects (realism, immersion, and sense of presence). In this manner, if results are successful, it is demonstrated that the vest can be integrated into any VR system, but also into other HMI systems with slight modifications.

In summary, this dissertation reports the development of a haptic vest from scratch, selecting and configuring all their components (tactile, thermal, and impact actuators) and driver systems in order to handle and synchronise its operation together with a VR system. Psychophysical experiments are necessary to understand how the torso detects the stimuli that the vest can render, ascertaining parameters to distribute the actuators in the entire vest, and create optimal haptic patterns. Once completed the design, the haptic vest is

validated to ensure the whole system operates flawlessly and, lastly, several experiments are conducted to determine the influence of haptic feedback when the vest is integrated into a VR system, both on its own and operating along with other haptic devices.

The reported works have been related strictly to the European Project AUGGMED (Ref: 653590, www.auggmed-project.eu). All VEs were developed within the framework of this project, and the initial requisites of the haptic vest were linked to the original requirements of those environments. The haptic vest evolved to be general-purpose, versatile, and applicable for any HMI system, even though its specific purpose still is the integration into VR systems. The dissertation describes two versions of the vest, which were validated in the AUGGMED pilots with satisfactory assessments by end-users. Those rewarding assessments repeated during the final evaluation by the European Commission at the end of the project, coinciding with results stated in the next chapters.

1.2 Motivation

From its beginning, this work is related unyieldingly to VR since the haptic vest aims to enhance the perception of virtual scenarios. Despite this first approach, the haptic device can also be integrated into whichever HMI system. VR or HMI systems usually focus their efforts on displaying impressive virtual effects to allow users to feel that they are visualising a real world, even when they are wholly aware that the world is virtual. Those systems also commonly render reliable auditory effects to boost the immersive sensations in the VE. However, the sense of touch generally remains in the background since most of the systems do not include haptic feedback. The environment hence does not involve users wholly, which might entail losses of realism or immersion, increasing the likelihood that the application in question does not fulfil their primary objectives.

The sense of touch is essential in daily life. It provides crucial information about the surrounding environment, and without it, people could not deal with everyday situations adequately during the day since they cannot receive that information through no other human sense. Likewise, if people miss the touch when they are coping with a VE, users may experience unlike sensations regarding a real situation, and the performance of the system might be lower. Otherwise, if the system includes haptic feedback, users are more comfortable, and they fulfil more easily the objectives of the system.

Some VR or HMI systems include haptic devices mostly for hands, whereas the rest of the body is mostly unexplored [6] [7]. Nevertheless, the torso, the legs, or the arms can become a source of information as powerful as the hands, even though the more dependable solution might be the combination of all possible devices (stimulating several areas in the body) to get the more resembling situation to a real environment.

The vest is conceived originally to use alongside VEs for the training of first responders,

such as military forces, medical teams, or police, among others. Those environments seek to simulate dangerous situations, which cannot be simulated in reality, for instance, a terrorist attack. The objective in those environments is that users conduct some prearranged tasks similar to the actions they would have to do in a hypothetical real situation. However, most of current VR systems only allow to watch and hear the virtual scenario, but haptic feedback lacks, becoming a hinder to achieve the best performance during virtual training. In this manner, a haptic vest might entail a leap of quality in order to approach the virtual scenarios to reality. If VR systems use all kinds of feedback (visual, auditory, and haptic), users feel completely immersed, and they can fulfil the objectives of the training with easiness.

However, the creation of a haptic vest requires knowing how the sense of touch works and how it detects real sensations in order to create haptic stimuli as close as possible to those real stimuli. The torso is an unexplored area so far, and there are barely studies about haptic perception as regards other body areas. The objective is to create a device to stimulate dependably the torso and, thus, it is necessary to study haptic perception so as to obtain the relation between the features of actuators to the stimulated areas, which afford to develop reliable haptic stimuli. Thereby, the results serve to create a haptic map of the torso, which it is useful to design and develop the haptic vest, besides achieving the stimuli convey adequate information from the virtual scenario to users through the vest.

How check that the developed device fulfils the initial objectives? It is necessary to conduct experiments to ascertain the validity of the completed development. The device must stimulate the users' skin appropriately, enhancing the capabilities of the VR system in which the vest is a component. It is even feasible to combine the vest with other haptic devices focus on other body areas, verifying if the merge of several devices (e.g. a haptic vest and a fingertip haptic device) may foster the benefits of haptic feedback in virtual experiences.

Ultimately, the motivation is to achieve a stunning breakthrough in the development of haptic devices for VEs, paying particular heed to the perception in the torso. This dissertation reports the steps to ascertain unknown aspects of haptic interfaces in the torso and its subsequent applicability in VR systems. All those aspects may be conspicuously helpful for years to come owing to the astonishing growth of VR and derived devices, which will be part of the daily life sooner rather than later.

1.3 Objectives

The first main objective of this thesis is to create a haptic vest to integrate into VR systems. Furthermore, there are some additional objectives such as the creation of a haptic map of the torso to base the vest's design, or the evaluation of the haptic vest while operating alongside VR systems. The objectives of this thesis are summarised as follows:

- The design and development of a haptic vest that is capable of integrating into VR systems. It must stimulate users using easily recognisable stimuli (tactile, thermal, and impact feedback).
- The creation of a haptic map of the torso, which must comprise several psychophysical parameters (both tactile and thermal), revealing the particularities of haptic perception in the torso. Those parameters serve to design the haptic vest and to create haptic patterns with which stimulate users dependably.
- The validation of the haptic vest to ascertain if it renders vibrotactile, thermal, and impact feedback appropriately. Results report the required enhancements to improve the subsequent versions of the vest. Employed methods may be useful for validation procedures in similar devices.
- Preliminary evaluation of the haptic vest, seeking to achieve a proper integration of the vest into a conventional VR system. Participants assess the operation of the vest and its influence in the virtual scenario employing subjective measures. Moreover, the experiment also serves to ascertain if the previous expertise of users with similar systems influences positively or negatively in the virtual experience.
- Final evaluation of the haptic vest, which must focus on revealing the influence of the vest in stressful and unfriendly virtual experiences. In this case, participants assess through subjective and objective measures.
- Evaluation of a full-body haptic device by including a fingertip device is the first step to create a full-body haptic device to stimulate the entire users' body during a virtual experience. The experiment seeks to ascertain the likely benefits for users by using the joint system composed by the conventional VR system, the haptic vest and the fingertip device.

1.4 Outline

This thesis consists of an introduction to show an overview of the whole dissertation. Next, a general description of haptic perception, and the state of the art of haptic and VR devices, as well as the standard methods to assess VEs. Then it presents the creation of a haptic map of the torso on which to base the design and development of the haptic vest. The device is validated afterwards to ensure proper operation, and it is finally evaluated when it is integrated into three different VR scenarios by using diverse assessment methods. The outline of this thesis is at follows:

- Chapter 2 presents concepts about human haptic perception, focusing particularly in the torso. It also presents the state of the art about haptic devices, VR systems, and common methods to evaluate VR environments and the users' experience.
- Chapter 3 describes the design and the development of the haptic vest. It describes the selection of all haptic actuators, the methods to handle the operation of every actuator, and the general control of the vest, that allows its integration into whichever VR system.
- Chapter 4 describes the creation of a haptic sensory map in the torso. It describes the conducted psychophysical experiments, and the two objectives of the sensory map: the distribution of actuators in the vest, and the creation of haptic patterns to convey information from the VE to users through the haptic vest.
- Chapter 5 describes the two first iterations in the evaluation of the haptic vest. Experiment 1 validates the three feedback systems in the vest (concerning their operation and configuration), and if the vest is ready to integrate into a VR system. Experiment 2 seeks to validate the integration of the haptic vest into a conventional VR system and ascertain the dependency of subjective perception on the previous expertise with haptic or VR technology. Both experiments yield required actions to enhance the future versions of the vest, furthering inadequate or detrimental aspects for the users' experience, the performance of the VR system, or the accurate haptic stimulation by employing the haptic vest.
- Chapter 6 describes the two final iterations in the evaluation of the haptic vest. Experiment 3 employs a complex VE, and a broader assessment consisting of subjective and objective measures. Results yield how users interact with the VR system, and how the definitive version of the vest affects the virtual experience. Experiment 4 includes a haptic fingertip device, seeking for full-body haptic feedback, and to analyse how it affects the perception of the virtual scenarios. These experiments include all identified improvements in the previous chapter, and results report the definitive outcomes about the whole development of the haptic vest and its integration into VR systems.
- Chapter 7 reports the conclusions of the conducted works in the entire dissertation. It states the comparisons between the initial objectives and the achievements after developing, validating, and employing the vest integrated into VR systems.

Chapter 2

State of the Art

The sense of touch allows for perceiving an object by touching or making contact with its surface. This sense affords to examine their main features such as the texture, the shape, the temperature or the exerted pressure when an object is being manipulated. The perception begins when whichever part of the human body surface makes contact with the surface of any element. Those contacts usually take place using the hands or the fingertips since they are the body areas which more often interact with the surrounding environment [8] [9].

The sense of touch is essential during daily life because it provides an enormous and continuous amount of information and, hence, it becomes a beneficial asset to cope with all kind of everyday situations. However, the sense of sight or the hearing provide larger quantities of information and, despite its proven importance, the sense of touch is frequently set aside during the perception in HMI systems. VR systems are a conspicuous example since the prevailing stimuli are visual and auditory, expelling the sense of touch to the background, even though it could be indispensable to engage the full details of daily situations.

It is at this point when the term 'haptic' takes on interest, and it is necessary to go back to ancient Greece in order to find their etymological origins: the word 'haptesthai' meant 'able to touch' in ancient Greek [8] [10]. This word underwent an evolution over the years until converting into the word 'haptikos', whose meaning also contained the concept of grasp [11]. Those two terms evolved during the subsequent centuries until the coinage of the term 'haptics', referring to the capability of perceiving contacts or forces through the human sensory system.

The current concept of haptics is further divided into two sub-terms, namely: cutaneous perception (touches or tactile stimuli) and kinaesthetic perception (forces). A haptic device is a mechanism capable of creating diverse interactions via the skin, both cutaneous and kinaesthetic [12]. Therefore, a VR system must include haptic systems so that users perceive via the sense of touch, accomplishing the simulation of three out of five human senses. In this manner, more simulated senses may lead to higher levels of VR system quality, and virtual scenarios become remarkably similar to any real environment.

This chapter sets some basic premises to understand the relation between haptic devices and the sense of touch. The first step is to analyse the configuration of the sensory system and the mechanisms used to accomplish perception through the sense of touch. It is then also required to understand how to characterise haptic perception and how the results serve to design haptic devices in order to simulate tactile stimuli dependably.

The next step consists in setting forth the current state of haptic technology, analysing the main trends on the development of mechanisms and devices, as well as stating systems akin to the designed haptic vest. The following sections also expound the last advances on VR systems, their derived technologies and the relationship to haptic devices. The application of these devices usually results in enhancements of both the quality of VR systems and the user's experience.

Finally, it is crucial to evaluate the usage of haptic devices together with VR applications. There are two conventional assessment methods: questionnaires or physical and physiological user's responses, although both pursue to settle the influence of haptic stimuli in a VE. The last section reports a brief review about both assessment methods, aiming to analyse the quality of the whole system with particular attention to the ability of haptic systems of rendering stimuli stemming from a VE.

2.1 Sense of Touch

Before going into detail about haptic devices, it is unavoidable to put forward some basic concepts about the sense of touch and the body mechanisms involved in the perception of external stimuli through the skin. The objective is to gather knowledge to accomplish a proper configuration of haptic devices in order to simulate dependably the real interactions using haptic stimuli.

The first step is to study the skin, paying particular heed to its structure and their main operating features. The skin is the most extensive system of the human body, and joined together the skin appendages, comprise the integumentary system, whose functions are wide-ranging such as thermoregulation or protection against noxious external agents [13]. However, the most critical function regarding haptic technology is the ability to perceive cutaneous, kinaesthetic, and thermal stimuli through several receptors distributed in both outer and inner layers of skin [14].

The sensory receptors are distributed in the two upper skin layers: the dermis and the epidermis [13] (see Figure 2-1 for all details about the explanation of receptors in skin). On the one hand, the epidermis is the more external layer, and its primary purpose is to protect the body employing cells known as keratinocytes, although this layer also contains one kind of receptor: Merkel cells. On the other hand, the dermis is the layer immediately below, and it has more functions such as protection against mechanical injuries, water repellency

Figure 2-1. General structure of the skin, differentiating between the hairy and glabrous skin. The most common mechanoreceptors are classified according to the adaptation velocity when a stimulus activates them [15].

or body thermoregulation. Nevertheless, the primary function is the perception since this layer contains the majority of receptors, namely: mechanoreceptors (Pacinian, Ruffini and Meissner receptors), and thermoreceptors. Both layers are coupled, and they cooperate in repairing and remodelling the skin continuously. Finally, the last layer is the subcutaneous fat which provides firmness and hormonal functions but without an active role in perception [14].

There are several kinds of sensory receptors: mechanoreceptors (to perceive cutaneous or tactile stimuli), thermoreceptors (to perceive thermal stimuli) and nociceptors (to perceive painful stimuli). All of them are primary afferents or neurons whose essential function is to convert a stimulus into electrochemical energy through a procedure known as sensory transduction. This process occurs when a stimulus generates a potential in the receptor greater than a threshold. Once the activation takes place, the central nervous system transmits the energy until the brain, which decodes the signal into a specific stimulus that the person perceives over the skin [15].

A crucial aspect to consider is the different response velocities of receptors, hinging on fibres adaptation promptness. There are two alternatives: the slow fibres respond after an average time from the application of a stimulus over the skin; whereas the fast fibres respond rapidly after setting off a tactile stimulus [13].

Another aspect to ponder is the distribution of receptors in each body area since the hands or arms contain a larger quantity in comparison with other areas such as the torso, the back or the legs [15]. Thus far, this fact has entailed that most of the studies about haptic perception and the development of haptic devices focus on areas with more receptors and, consequently, with a higher resolution of perception [16]. Thereby, there is an absence of studies dealing with the covered areas with a haptic vest, so it is required to conduct some additional researches to obtain accurate data for an appropriate design.

2.1.1 Mechanoreceptors

The activation of mechanoreceptors takes place when an external object displays mechanical energy over the skin, for instance, a vibration or a pressure. Even though all of them play a role in perception, the most relevant are Pacinian corpuscles, Merkel discs, Meissner corpuscles, and Ruffini cylinders [16].

It is vital to establish the differences among receptors since each one has different functions and trigger mechanisms. The Pacinian corpuscles are located in the deepest part of the dermis of glabrous and hairy skin, and they are spread widely over the torso. They have fast activation fibres and decode vibration or tapping sensations between *40* and *500 Hz*. Furthermore, the required amplitude to detect stimuli is *28 dB* (this value refers to a reference stimulus of *1 g (m/s²)*, which is a usual measure of amplitude). Hence, all stimuli must be superior to that activation threshold so as to initiate the transduction procedure.

Aside from Pacinian receptors, Meissner corpuscles also have fast adapting fibres, and they are also located in the dermis, although only in non-hairy skin. In this case, the receptors aim to localise the stimuli or to perceive beats and taps comprised between *3* and *100 Hz*. Their activation threshold is similar (around *28 dB*), so they need resembling activation to initiate the transduction procedure [15] [16].

Contrarily, Merkel discs have slow activation fibres besides a small field of action. They are located in the juncture of the dermis and the epidermis but only in glabrous skin. They aim to detect orthogonal pressures over the skin, provided that the contact frequency is between *3* and *100 Hz*. Moreover, just as Meissner and Pacinian corpuscles, its activation threshold is about *28 dB* [15] [16].

Ruffini cylinders are the other receptors with slow adapting fibres and, although they are located in the dermis and all kind of skin, they are only on the hands. The cylinders are activated when the skin is stretched or rotated with frequencies comprised between *15* and *400 Hz*. They further have a singularity since the stimuli only activate the transduction if the stimulus occurs at a certain distance from the receptor. Notwithstanding, the perception is more straightforward since the activation threshold is about *10 dB*, significantly lower than the rest of mechanoreceptors [15] [16].

In summary, any skin stimulation affects all receptors previously defined. For instance,

Figure 2-2. Common response of thermoreceptors. The typical activation temperatures for both cold and warm receptors are within the range 20 to 50°C . Cold receptors activate at temperatures below 30°C , whereas warm receptors activate at temperatures up to 45°C (before the nociceptors are activated) [15].

Pacinian corpuscles are the main involved to perceive a vibration motor operating at a specific frequency (among 40 and 500 Hz). Similarly, that vibration also generates a small pressure perceivable by Merkel discs; the Meissner corpuscles might locate the spatial stimulus origin, and, if the vibration produces a skin stretch, the Ruffini cylinders activate as well.

2.1.2 Thermoreceptors

The thermoreceptors are nerve endings which respond to temperature variations above the skin, both risings and drops. On the one hand, the rises activate the warm fibres whose response range is comprised among 30 and 48°C , but they are commonly enabled when the temperature is above 36°C (i.e. the ordinary body temperature), keeping them active until the temperature decreases to a value below the lower range limit (30°C). On the other hand, the cold fibres have the same response procedure although, in this case, the activation takes place when there is a temperature decrement in the range comprised among 5 and 45°C [15] [17]. The warm fibres have a more significant influence in perceiving temperatures above 36°C , even though the cold fibres also activates within that range (see Figure 2-2).

Despite the ranges of action for warm and cold fibres, the variation is not customarily appreciated when values are among 30 and 36°C since the usual skin temperature shifts between 32 and 36°C throughout a day [15]. Hence, an artificial hot stimulus has to be over 36°C to be noticed, but a regular user is capable of noticing a cold stimulus when the temperature is below 30°C .

This kind of receptors is not evenly distributed in the entire body since, for instance,

the hands or the fingers have a higher quantity of thermoreceptors than the back or the abdomen. Another factor to contemplate is cold fibres are more numerous than warm fibres (the ratio is 30:1), which causes a better response and a furthered perception when a cold stimulus is applied [17].

Finally, another noteworthy difference between fibres is its response velocity because the time to activate thermoreceptors depends again on the fibres ilk: the warm fibres take *1-2 m/s* whereas the cold fibres take *10-20 m/s*. Therefore, cold stimuli are also more swiftly perceived than warm stimuli [16] [17] [18].

2.1.3 Nociceptors

The painful stimuli generated over the skin unleash the response of nociceptors, which may set off damages over the skin and the body tissues. There are three types of nociceptors: thermal (they respond to painful thermal stimuli), mechanical (they respond to painful pressure stimuli), and polymodal (they respond to high intensity mechanical, thermal or chemical stimuli) [15].

There is a noticeable relation between thermoreceptors and nociceptors: if the skin temperature exceeds *45 °C* or decreases below *15 °C*, both thermal and polymodal nociceptors might activate. However, when the warm or cold fibres stop its operation, the nervous system activates the nociceptors, although there are differences in the disabling procedures of thermoreceptors. The warm fibres disable instantaneously by reaching the upper limit (*45 °C*), but the cold fibres experience a gradual disablement which begins when the temperature decreases as of values about *18 °C*, so the pain sensation due to cold stimuli takes longer times to be perceived [16] [17].

Likewise, it is crucial to maintain some precautions when mechanical stimuli are applied over the skin, handling them not to go over the mechanical intensity thresholds to avoid damaging the skin. If the stimuli reach upper values than those strength limits, the skin might be damaged, producing inflammatory responses and releasing chemical components that may occasion edemas or skin redness, among other effects [15].

2.1.4 Active and Passive Touch

Both the sense of touch and the haptic technology are distinguishable according to the stimulation ilk, that is, active or passive stimulation. The active touch comes about when users handle the stimulation, whereas they receive stimuli without controlling them when the touch is passive. Active haptic devices are created for hands or arms because they help to explore a remote or virtual object actively, whereas passive devices render the stimuli provided by an environment over whatever body area [13].

Therefore, it is simpler to create active stimuli for haptic devices since they may create familiar memories on users because they are accustomed to exploring objects actively and,

hence, those users may recognise the stimuli with easiness. However, it is harder to reproduce faithfully events stemming from a VE using passive stimuli, hindering the development of appropriate haptic patterns for stimulating users and leading to the current scarcity of exclusively passive devices [13] [19].

2.2 Characterization of Haptic Stimulation

The haptic stimulation is closely related to the trigger mechanisms of body receptors (perception and discrimination thresholds). Although there are several psychophysical parameters to consider, the spatial acuity is undoubtedly essential, both vibrotactile and thermal. Values of spatial acuity allow distributing the actuators properly in order to get the best performance of the haptic device.

However, the most of studies about vibrotactile spatial acuity are focalized on hands or arms [20] [21] [22], even though the buildup of haptic devices for all body areas has unleashed a proliferation of studies over the torso [23] [24], the back [25] or even the head [26]. Not only do these studies determine the spatial acuity, but they also prove the differences owing to the type of actuator [27] or the possible variations after continuous training [28].

Likewise, there are few studies about thermal spatial acuity, presumably due to the scarcity of both thermal actuators, and haptic devices which include thermal feedback. Other phenomena such as the spatial summation might be a leading reason for that scarcity. It may cause a flawed identification of stimuli or misunderstandings, confusing the information that a stimulus attempts to transmit [29].

Nevertheless, the spatial summation does not only affect thermal perception but also affects considerably to vibrotactile perception. This phenomenon generally comes about when two nearby stimuli are applied over the skin simultaneously, generating a more powerful stimulus than the originally intended.

The summation of vibrotactile stimuli originates in Pacinian corpuscles; thus, the effect is more significant over areas with larger quantities of these receptors [30] [31]. These corpuscles are the principal involved in vibrotactile perception over the torso (the rest of mechanoreceptors are distributed barely over those areas [32]); thus, the summation phenomenon must be considered to develop the haptic vest appropriately. The main consequence of this phenomenon is a deviation of spatial acuity depending on the stimulus intensity and the area wherein the stimuli are displayed. The summation extends the area where a person notices the vibration according to the rise of intensity and, in turn, that generates a decrease on spatial acuity values [33] [34] [35]. The spatial summation is only triggered when the frequency is higher than 25 Hz [36], and this effect is considered solely when the vibration operating frequencies exceed that minimal threshold [37].

The spatial summation of thermal stimuli has similar inferences about the area and the

spatial acuity but, in this case, the phenomenon depends on the intensity of the thermal stimulus. Some studies stand out the influence of neuronal summation as well, revealing that this effect does not wholly originate in thermoreceptors, but it also hinges on the transduction procedure, entailing a summation even when the stimuli are not close to each other [31]. This phenomenon may unleash undesired heating or cooling when the system displays several stimuli simultaneously. Thus, it is an aspect to consider during the creation of thermal patterns to prevent uneasy or painful sensations over users.

There are additional parameters which influence the thermal summation and, therefore, the thermal spatial acuity. Each body area has a different skin composition, and some zones have a bare concentration of thermoreceptors, which may smooth that phenomenon [38]. Similarly, the spatial summation is stronger with warm sensations as regards the cold ones [39] [40]. Thereby, the driver systems must always control thermal stimuli to avoid the activation of nociceptors and mitigate the detrimental effects and painful sensations derived from thermal summation [41].

In summary, the spatial summation has notable importance to develop haptic devices. This concept and the spatial acuity are essential to accomplish an adequate distribution of haptic actuators in whichever device. If that distribution is not appropriate, users would not recognise the stimuli satisfactorily, which might lead to misunderstanding haptic stimuli [42].

It is also essential to establish some detection thresholds for both vibrotactile and thermal stimuli. On the one hand, the absolute thresholds allow for determining the minimal intensity to perceive a stimulus over the skin. On the other hand, the differential thresholds indicate the required intensity difference amid two consecutive stimuli to notice them as distinct stimuli.

As the case of vibrotactile spatial acuity, there is a significant quantity of researches about vibrotactile absolute and differential thresholds but chiefly focalised on hands, and arms [43] [44]. Those studies assess both the active touch (to analyse the perception of textures [45] or forces [46] [47]) and the passive touch (aiming to investigate the perception of displayed stimuli over the skin [43]). These experiments are infrequent above other areas since most of the haptic devices primarily focus on areas with higher sensitivity and larger quantities of receptors, either mechanoreceptors or thermoreceptors. However, there is an emerging interest during the last years, attempting that these devices become widespread and reach the general public [48].

In contrast, absolute thermal thresholds are mainly limited by the activation values of thermal and polymodal nociceptors since all stimuli within the range mentioned above ($15 - 45^{\circ}C$) are readily perceived [17], so there is no necessity of additional studies.

Nevertheless, there are plenty of studies about thermal differential thresholds, but once again mainly focused on hands and arms [29] [49] [50] [51]. Those thresholds are generally

rather low, which imply the body has high capability of noticing the changes in temperature provided they are prompt [17]. If the changes are lower, the body continuously adapt itself to the stimulus, and users perceive toughly the successive changes (the user requires a significant change to perceive a difference) [29]. Moreover, the studies demonstrate the differential thresholds are lower with cold stimuli, evidencing that a higher quantity of fibres (the ratio is 30 cold fibres per one warm fibre) entails a more precise perception [29] [52].

Summarising, the lack of studies about vibrotactile absolute and differential thresholds in the torso indicates the necessity of additional researches to obtain the required values to create appropriate haptic patterns. Contrarily, these aspects have been studied thoroughly regarding thermal perception, and it is feasible to use outcomes from previous researches. The spatial acuity values for vibrotactile and thermal perception in the torso are required as well, seeking the values for adequate positioning of every actuator in the haptic vest.

2.3 Haptic Devices

The objective of haptic devices is to simulate cutaneous, kinaesthetic, or thermal stimuli so that users are capable of perceiving virtual or remote events via the skin; thus, the perception mechanisms reported in the previous section must be carefully borne in mind. A haptic stimulus attempts that users can recognise physical contacts, hints to carry out a movement, blows, along with others. Haptic systems are wearable devices since they have to be permanently in contact with the body in order to activate the skin receptors properly. Once the activation takes place, the human sensory system set off the sequence of events resulting in the correct identification of a specific stimulus.

Although there is a large number of applications which make use of haptic devices, most of the current designs focalise on providing additional stimuli in numerous situations such as the control of a remote system, the teleoperation of robots in dangerous environments [53] or the guide of blind people in its daily life [54]. The primary purposes of using haptic technology are related mostly to the enhancement of the interaction with VEs [6] [55], providing more information about the scenario [56] or improving the realism of the system by adding tactile stimuli [57], provided that all considered VR systems already include visual and auditory feedback.

2.3.1 Active and Passive Devices

The previous section addressed the difference between active and passive touch. Those definitions are readily expandable to haptic devices, discerning between active and passive devices. Figure 2-3 shows two devices: one of them is active (a finger device with vibrotactile and thermal feedback), and the other is a haptic vest to perceive stimuli from VEs (passive device).

Figure 2-3. Vibrotactile and thermal device for the finger which afford to interact through the active sense of touch (left image) [72]. A haptic vest for serious games, which afford to notice haptic stimuli coming from VEs by means of passive sense of touch (right image) [73].

The active haptic devices allow for exploring virtual objects with the hands [58] or manipulating objects remotely, perceiving its weight or texture [59]. These devices always seek the most realistic and dependable interactions so that users carry out tasks in a VE as if they were in a real scenario. It is thus straightforward to find plenty of applications pursuing to improve hands or arms interactions since they are the body parts usually employed to handle objects of a real environment [7]. Thereby, most of the applications attempt to enhance the efficiency of the system so that users notice artificial stimuli as realistically as possible. For instance, there are plenty of applications related to medicine in order to ease the interaction with fragile tissues or improve exoskeletons' performance [60] [61] [62].

According to the literature, the fingertip is the hand's region with higher sensitivity, so many devices focalise uniquely on its stimulation. Some examples are mechanisms for the discrimination of virtual objects as well as their shapes, the reception of signals through skin displacements, or the use of complex haptic cues as help for manipulation tasks [58] [63] [64]. Conversely, hand devices are based usually on gloves with tactile feedback [65] [66], although there also are systems to create both cutaneous and force feedback in order to facilitate grasp tasks [6] [67], or devices which help users to perceive textures of a surface [68] [69]. However, haptic feedback over the arms is commonly associated with exoskeletons or sleeves oriented to diverse practices such as training or rehabilitation [70] [71].

There are additional methods to accomplish haptic feedback such as electrostatic devices, although they also predominately focus on hands' applications [74] [75]. Furthermore, there are alternate methods which operate employing external modules that create feedback when the users place their hands or arms closer to the device field-of-action, for instance, ultrasounds systems [76] [77] or air stream devices [55].

Conversely, passive haptic devices allow for stimulating whichever body area. In this

case, users do not cause contact with the virtual or remote elements, but they notice stimuli emerged from the environment not directly created by themselves. It is not difficult to find developments for the torso which are frequently focused on navigation throughout real or virtual scenarios [78] [79] [80], simulation of movements [81] or touch therapies [82]. There also are designs of devices for feet or legs in order to interact with VEs or robots [83] [84] [85] [86], even they are markedly scarcer.

Haptic devices are customarily composed of several kinds of actuation aiming to create multimodal devices capable of rendering complex stimuli provided by a virtual or a remote environment. In such a manner, the main objective of these devices is that users perceive several simultaneous stimuli over a specific area with high degrees of realism. Most of these devices are regularly composed of tactile feedback and some additional actuation systems such as force feedback [87], thermal [88] [89], or impact [57], among others.

There are various multimodal passive devices just as the haptic vest presented throughout this thesis, even though the designs are assorted from belts to shoulder straps, covering only some regions of the body [79] [82]. However, the majority of devices are whole vests oriented to various applications such as research tasks [56] [90], VR or military applications [91] [92] [93]. Practically the entirety of designs has appeared during the last years, seeking to enhance VR experiences, encountering devices focused exclusively on specific applications such as training [94], or versatile devices which serve for countless applications [57].

2.3.2 Vibrotactile Feedback

Haptic devices commonly make use of vibrotactile actuation to create tactile sensations through the skin, either with active or passive devices. Most of the current haptic devices are based on studies about the vibrotactile perception and the operating mechanisms of standard actuation systems [95] [96].

The vibrotactile feedback may be applied practically all over the body, so it is effortless to find systems to display stimuli on the hands [97], the feet [98] or the torso [99]. The devices which include vibrotactile actuation provide the possibility of modifying operating parameters such as temporal frequency, amplitude or force. In light of these apparent benefits, these devices have countless applications such as information transmission [100], texture perception [101], assistance of blind people [102], or object manipulation [103]. Figure 2-4 shows two devices, including vibrotactile feedback with different objectives.

Almost all of the previous examples make use of vibration motors as its vibrotactile actuation system since they provide high versatility and are capable of creating varied haptic stimuli with a single kind of motor. Even so, tactile stimuli can also be displayed employing alternative methods, for instance: audio systems or speakers, linear actuators (solenoids), piezoelectric actuators, electrostimulation systems, or new technologies as wires of shape-memory alloys [92] [95] [102].

Figure 2-4. Tactile screen device, in which the pen displays tactile feedback over the fingers when it touches the screen (left image) [104]. Chair with several vibrotactile actuators which allows for perceiving haptic patterns over the back while the user is seated (right image) [105].

Once the design and build of a haptic device are definitive, the more critical aspect is to configure the actuation systems in order to ensure the perception of stimuli accurately. These devices display those stimuli employing haptic patterns, whose creation can gear towards rendering realistic stimuli, navigation cues or spatial hints, among others.

The creation of patterns consists in modifying the operating parameters of actuators so that users can adequately interpret the patterns wholly [106] [107]. In the particular case of vibration motors, the procedure of creation attempts to generate vibrotactile sequences which users can understand as a virtual interaction or a texture when they touch an object [108] [109]. There also are some tools to automatically create those patterns in order to ease the merger of a particular haptic device with whichever application [110] [111].

2.3.3 Thermal Feedback

It has not probably been as explored as vibrotactile feedback, but thermal stimuli also have an essential role in haptic systems since a person perceives continuously thermal sensations through the skin in daily life. Therefore, the thermal feedback is vital to dependably simulate a realistic VE since it furthers the perception of changes in temperature, the typical ambient temperature or the occurrence of dangerous events such as a fire or an explosion.

Thermal devices are usually merged with vibrotactile systems [112] [113], or even with force feedback [114], which provides options to create combined stimuli and to improve the user's experience in diverse systems such as VEs or medical applications [89] [115] [116] [117]. Figure 2-5 shows a standard thermal device for a single finger.

Most of these systems employ Peltier cells since they allow for rendering hot and cold stimuli. These thermal actuators require some additional elements to achieve optimal operation. On the one hand, they need both a heat sink and a driver circuit to handle the temperature rendered by the cells so that they reach and maintain the target tempera-

Figure 2-5. The thermal device allows for perceiving thermal (using the thermal pad) and vibrotactile (using the texture display) stimuli over the fingers. The system also contains a thermal sensor to control the temperature displayed over users at every moment [113].

ture with minimal errors, also avoiding reach temperatures beyond the pain limits given by the nociceptors [112] [115]. On the other hand, the temperature control system must be swift and robust; in such a manner, the haptic vest can render variations in temperature accurately [118]. In this case, it is also feasible to create haptic thermal patterns to help users to identify particular stimuli, but no many developments are pursuing those objectives currently [117].

2.3.4 Impact Feedback

The haptic vest in this thesis includes a system to create impact feedback. There are no many methods to generate those impact stimuli, even though some studies have profusely researched on this topic during the last years. In most of the cases, haptic devices which include impact actuation also contain other kinds of feedback, seeking multimodal systems to create the best user's experience [119].

There are some developments of devices capable of creating physical impacts but mostly using muscular electrostimulation systems (see Figure 2-6) [120], which simulate the sensation by tightening the affected muscle [121] [122].

Nevertheless, there also are some mechanisms which create the impact using a mechanical system, for instance, devices which simulate the mechanism of a firearm. There is currently diverse research about those systems for mobile devices applications under purely mechanical systems [123] [124] or combined with vibrotactile actuation [125].

Figure 2-6. The impact system for the arm allows for perceiving impact feedback using EMS. This system is usually used alongside a VR system [120].

2.4 Virtual Reality

The '90s marked a milestone on the development of VR technology which meant a growth of studies dealing with this topic besides their related systems. Thenceforth, there has been a continuous proliferation of commercial and research developments, attaining systems with a startling graphic quality or enhanced capabilities of interaction thanks to the evolvement of novel modes of sensory stimulation [126]. The current systems allow users to perceive a VE as if it was a real environment, in other words, the users can do the same tasks or develop the same feelings or thoughts than in a real situation [127] [128].

Practically whichever contemporary VR system is composed of a virtual scenario wherein users must carry out diverse tasks to accomplish an objective while they cope with the events occurring around them [129]. An example can be a scenario where users have to disarm a bomb besides interacting with a detonator and deciding if they cut the red or the black cable.

Therefore, it is utterly needed an optimal visualisation system in order to get stereoscopic vision which allows users to inspect the scenario adequately. The most usual device is an HMD which further serves to keep users apart from the real world so that they can entirely focus on the VE. The second requirement is an audio system in order to hear the auditory stimulus in the virtual scenario so that users can acquire the maximum amount of information provided by the VR system. Furthermore, it is required a device to control the virtual avatar such as controllers, a tracking system for the hands or the whole body, or a system combining both: the tracking system and controllers. The final aim is to integrate all those addressed components to accomplish a system which creates wholly immersive and multisensorial experiences [129].

Nevertheless, there are variants beyond the pure VR but focalised on the virtualisation

Figure 2-7. Conventional virtual environment, in which users can write over a virtual board using a virtual chalk [140].

of the real world. Both the augmented and the mixed reality systems seek the interaction with a real environment which has some additional virtual elements [130]. There is a critical difference since the mixed reality allows the interaction or manipulation of real visible objects in the virtual environment [131], whereas augmented reality only allows the visualisation of real elements. Both technologies have thrived alongside the VR, emerging a great variety of developments and applications during the last years [132].

2.4.1 Multimodal Systems

The current VR systems are capable of stimulating both the sense of hearing and sight. The more immediate step is the addition of stimulations through the sense of touch using haptic feedback. This fact might cause an enhanced user's experience in VEs since scenarios become more similar to reality. The ultimate objective is to obtain multimodal systems with the maximum number of available stimulation modes, that is, to use as many human senses as possible [133] [134], applying to virtual, mixed, or augmented reality. Figure 2-7 shows a typical VE wherein users can handle a piece of chalk to write.

Alongside the evolution of VR, there has been a continuous appearance of haptic devices aiming to serve as helpful tools for improving the performance of VEs, bringing about the emergence of the first standards about the relation between haptic devices and VR [135] [136] [137]. Nonetheless, the last decade has supposed the genuine rise of this technology, but always maintaining the same aim: to improve users' experience employing a VR system [138] [139], which have led to the proliferation of both research and commercial developments.

The integration of several feedback modes requires the VE displays all stimuli congruently together with virtual events; thus, users simultaneously visualise, hear and perceive (through haptic stimuli) a virtual event. In such a manner, the system must handle all stimuli without giving particular importance to any of them: visual, haptic or auditory [141]. If a VR system has high graphical quality, but the rest of feedback does not fulfil the prearranged requisites,

Figure 2-8. Standard mixed reality environment, in which users can see, using a HMD, their hands holding a tool to conduct some specific work [149].

the stimulations cannot reach the demanded levels of realism, and the multimodal VR system is pointless. Hence, both haptic and auditory feedback systems always require the utmost quality to create virtual stimuli adequately [142].

There also are ample quantities of haptic devices gear towards augmented or mixed reality systems, always pursuing the objective of improving the user's experience while they interact with virtual scenarios [143] [144]. The synchronisation between haptic systems and virtual scenarios also has a prevalent role since haptic stimuli must be congruent with the events stemming from the virtual world; otherwise, the system operation might markedly complicate. Some of the most remarkable examples attempt users may perceive whichever event provided by VEs, such as contacts, breezes or textures when exploring an object [145] [146] [147]; either in mixed [148] [149] or augmented reality applications [140] [150] [151].

2.4.2 Serious Games

Serious games are a leading application both for VR environments and haptic devices. They are VR systems specifically focused on tasks related to learning, training, education, or medical tasks, among others [152] [153] [154] [155], but they cannot be simulated readily in real life due to their exceptional features. A serious game recreates this kind of scenario, and a multimodal system which includes haptic feedback might help the users get used to those unusual situations. A haptic device may enhance the user's experience or the system's performance, aiming that users get on with easiness when they face similar real situations afterwards [156]. Figure 2-8 reports a mixed reality environment for training workers in an industrial environment.

The relevance of this research field in this thesis lies in the main objective of the designed haptic vest is its application along with a serious game, even though it is also applicable to whichever VE. The haptic device must strengthen some users' abilities to improve its performance in the VE, but also during similar situations in reality after the training. There already are some examples of serious games which make use of haptic devices to provide additional benefits for users [156] such as methods to improve spatial ability [157], reha-

bilitation of patients with various injuries [158] [159], or to prepare users for extreme or dangerous environments [73].

Although not strictly identical, the VR applications for entertainment are emerging concurrently to serious games. Even though these applications are not serious games, haptic devices are equally applicable for those systems, for instance, using a haptic glove with a videogame. It is straightforward to find some commercialised devices or in different stages of its development, pursuing the combination of haptic devices and VR systems become accessible for general public [160] [161].

In summary, the main niche of application for the haptic vest is VR systems, seeking to improve the user's experience and the performance of the system. Although there are relevant developments that go back up to twenty years [92], the technology has evolved until the current designs which focalise on entertainment applications or serious games (learning, training or professional applications) [57] [94] [162].

2.5 Evaluation of Haptic Devices and Virtual Reality

A system consisting of a conventional VR system and a haptic device requires an assessment to ascertain whether the integration is appropriately conducted, evincing if there are benefits for users during and after the experience. There are several methods to assess particularities of the integration which hinge on several aspects, such as the personal perception of the scenario or the stress suffered throughout the experience.

In this manner, the user's experience in a VE must be adequately assessed to ascertain the system's usefulness. The different measures provide information from several perspectives which, after a thorough analysis, can determine the condition of users when they are immersed in the virtual scenario. Both the gathered data and conclusions drawn from the analysis generate a general idea about the whole experience, from the quality of the virtual scenario to the usefulness of the haptic vest as a component of VR systems.

There are two main methods to assess these systems: on the one hand, subjective questionnaires in which users respond several questions about their sensations, focusing the attention in their perceptions, feelings, or thoughts during the whole experience in the virtual scenario (subjective assessments). On the other hand, the physiological measures which indicate the effects on the users' condition when they undergo changes related to distinct events during the virtual experience. Examples of those measures are the Heart Rate (HR) and its variability, the attention to the scenarios, or the involuntary physical responses to some virtual events (objective assessments).

Thereupon, the next subsections set forth the different kinds of existing measures and their particularities with detail, as well as the benefits and detriments for the assessment of multimodal VR systems.

2.5.1 Subjective Assessments

Subjective questionnaires are valuable in order to allow users to convey their perceptions, feelings and thoughts during the virtual experience. Nevertheless, they entail a significant problem since the users' responses are liable to be biased because the assessment depends on the particular perception of each user.

The bias on the answers can be related to diverse aspects such as the previous use of similar systems, or the users' propensity to feel comfortable using this kind of technology. Notwithstanding, these responses are still helpful since they provide a singular point of view of each experience. The most suitable solution is to complement the questionnaires with objective measures which are addressed in following subsections.

These questionnaires assess the sense of presence or the immersion in VEs, besides the realism of the physical scenario. Hence, before introducing the different variants, it is required to differentiate between the three concepts since they can be misleading frequently, avoiding likely mistakes to understand the results.

Realism

The realism of VEs is mostly related to the configuration of the scenario, in which the graphical quality has an especially noteworthy sway [163]. However, there are more aspects to consider such as the users' ability to identify themselves socially with the VE [164]; the similarity of the avatar behaviour in comparison with a typical behaviour in a resembling situation; the decision-making capacity during the experience; the VE authenticity; or the user engagement with the system [163]. Furthermore, there is a clear relation with the other two concepts because higher levels of realism usually entail an enhancement on the levels of both the immersion and the sense of presence noticed by users [165] [166].

There are many studies which prove the visual features have a dominant role on the realism of VEs, turning the graphical quality into the main parameter to consider for evaluating the user's experience [167] [168] [169]. Thereby, haptic devices are an additional stimulation mode which might also influence and enhance the realism of the system: on the one hand, haptic feedback entails an extra sense to the multimodality; on the other hand, appropriate feedback might substantially enhance the technical capabilities of the whole VR system [134] [169] [170].

Sense of Presence

The first definition of the sense of presence goes back to 1983, when Minsky established the term 'Telepresence' as 'the ability to interact without problems with a remote environment, given that they receive enough quantity of stimuli to consider they are undoubtedly present in that environment' [171]. The evolution of technology and the appearance of VR systems led

to apply the same definition for the first VEs (which are quite similar to remote environments after all) [172].

The definition of telepresence is mouldable, and it can be adapted for current VEs, redefining the sense of presence as 'the perception of being physically present in a virtual place as well as having the capability of interacting with the elements of that place' [168] [173]. This definition is ordinarily known as virtual presence in order to differentiate it from the definition of telepresence and its relation with remote environments [174].

Additionally, there are several factors which sway the sense of presence in VEs, among which some sensorial features have a significant role, such as the quality and congruency of visual, auditory or haptic stimuli perceived during an experience [172] [173] [174]. The ability to modify the VE must also be borne in mind, independent of the inclusion of haptic devices [174]. Moreover, the methods to create realistic virtual avatars give vital importance to the user's engagement with the virtual avatar through the self-representation of its own body (sense of embodiment) [173] [175].

The concept of presence can be subdivided into several key aspects, and each one encompasses some traits of the user's experience. Although there are several subdivisions, all of them coincide on distinguishing three main aspects: the 'physical presence' which refers to the sensation of staying and controlling a VE, while they omit the real environment where they are; the 'social presence' which refers to the capability of interacting with an environment, neglecting that is a simulated scenario (sense of agency); finally, the 'self-presence' which refers to the connectivity with the controlled avatar that, in turn, is significantly related to the sensation of self-consideration as a physical part of the virtual scenario [175] [176] [177]. Nevertheless, there are other subdivisions which put in some additional concepts complementing the fundamental definitions such as the 'co-presence' or the ability to manipulate the elements remotely; the 'hyperpresence' or the ability to perceive the stimuli more intensely than in a real environment; and the 'eternal presence' or the ability to feel presence when there is not any interaction with the scenario [175].

Regarding the essential aspects, self-presence is probably the most significant aspect to consider given the current trends in VR technology. Nowadays, the VR systems deal carefully with the relation between users and the controlled avatar and, more specifically, with the aspects related to the avatar personality or its behaviour (sense of embodiment) [178]. Therefore, the self-presence becomes especially essential since it entails a nexus of union between the physical and the VE [179] [180], paying particular attention to the avatar actions or the interactions with their surrounding virtual elements (sense of agency) [173] [179].

Immersion

The immersion is also closely related to the technical capabilities of the system but from a psychological point of view. There is a relationship between immersion and sense of presence, similar to the relationship between realism and immersion. However, the immersion differs depending on users, and its particular perception of a virtual scenario owing to it is a subjective measure. In this manner, if a technical aspect enhances the quality of the system, it could equally enhance the immersion since both concepts are closely related, even though it ultimately depends on how users perceive the VE [165] [181] [182].

The multimodality of the system is another aspect which strongly affects the immersion and the presence. Most of current VR systems only display visual and auditory stimuli; thus, the addition of haptic feedback may make a difference. Some studies demonstrate how the addition of haptic stimuli implies improvements in the immersion and sense of presence perceived by users [173] [183] [184], independent on the selected method to render haptic feedback [185]. However, it is not only limited to haptic stimuli, but the olfactory feedback may also be a helpful method to increase the presence, despite its stimulation carries with more significant hardships [186].

In short, if the entire system maximises the realism, the sense of presence, and the immersion; the user's experience must improve. Moreover, users can fulfil the entrusted tasks in the virtual scenario with easiness, its behaviour is akin to what they would have in a similar environment, the performance of the system enhances, and the VR system fulfils all their initial objectives [187].

Previous Questionnaires

The three concepts must be taken into account to assess VEs employing evaluation questionnaires. Although all surveys are subjective by definition, there are objective or subjective connotations depending on whether the questionnaires attempt to assess the realism or the presence, so it is interesting to perform separated evaluations and obtain less biased assessments. In this manner, results yield a general view of the entire course of the virtual experience from distinct perspectives [163] [182]. Even so, most of the extant questionnaires focus only on the presence measurement, forgetting the realism, the immersion or the influence of multimodality in VR systems.

The questionnaires for measuring the presence have approached from different points of view, and it is thus easy to find some examples going back to the emergence of the VR technology [188], but also current examples which approach from a more in-depth perspective, analysing more specific factors from the VE [177]. However, the most recent questionnaires are based mainly on the first approaches from the end of the '90s, such as the SUS questionnaire [189], the Presence Questionnaire (PQ), the Immersive Tendencies Questionnaire

(ITQ) [182], or the ITC questionnaire [190].

The questionnaires are normally composed of a series of assertions that users must respond using a Likert scale [191] to express its agreement or disagreement as regards the corresponding statement. Each assertion attempts to clarify factors related with the key aspects of presence (social, physical and self-presence), obtaining a widespread viewpoint of the complete user's experience [177] [182] [188] [189] [190] [192] [193].

Nevertheless, the extant presence questionnaires do not usually include an extensive section to assess the influence of haptic devices both in the VE and the user's experience [175], so it is needed to define some additional assertions in order to put into the previous questionnaires, pursuing the assessment of the system's multimodality. The objective is to establish a standard questionnaire for the assessment of sense of presence, immersion, realism and their relations with every aspect of VR systems.

2.5.2 Physiological Measures

Even though the evaluation questionnaires are a standard and helpful tool to evaluate a multimodal VE, they are subjective methods, and responses may be wittingly biased from two perspectives: positive responses to benefit the research results or negative responses to detriment the conclusions. Responses can also be non-wittingly biased due to, among other aspects, the previous experience of users with VR systems. Hence, it is utterly necessary an objective point of view to complement the subjective evaluation, comparing both assessments in order to study the differences and figure out if the user is biasing their responses, endangering the research. The aim is to measure some parameters of the user's state during the experiments: the physiological responses, the autonomous responses or the aftereffects.

Physiological Responses

Physiological responses are parameters which indicate the user's status during whichever daily situation [194] [195]. They are also a useful method to assess the users' condition while they experience a VE similar to a real one [196] [197]. The vital signs are examples of physiological responses such as the HR, the respiratory rate, the temperature or the blood pressure [198], although some additional signs can be equally used, for instance, the skin temperature or the Skin Conductance (SC) [199] [200]. All of them provide relevant information to analyse the user's experience and to obtain significant results when comparing with subjective measures.

The usefulness of these responses lies in the relation between them and the human emotions, so it must be a significant aspect to consider for assessing the VEs (e.g. a fear emotion may entail a rising on the HR). In this manner, the relation serves to readily evaluate since users should develop the same feelings than they experience during a real situation: a person can feel fear or anxiety during a real dangerous situation, thus if a VE replicates a

similar situation, the user may have the same feelings or thoughts and their physiological responses evolve similarly [201] [202].

The analysis of physiological responses must consider some factors which may affect the measurement procedures and the subsequent assessments. The prior experience with similar systems might remarkably affect the results since users do not have the same reactions of surprise, frighten or anxiety. The events stemming from the environment would not imply pronounced responses, and it could be harder to analyse the results and obtain proper conclusions [203]. However, it is not the only cause which generates the signal becoming softened, but this phenomenon is also caused due to the users' habituation after a period experiencing the VE since their reactions and feelings are less startling [196].

It is necessary a timeframe before beginning the virtual experience to obtain a baseline for the measures. This line indicates the usual status of users regarding the specific measure, serving as a reference to explain in detail risings or drops of the signal, and the relation of those diversions with virtual events [196] [204].

Among all the extant physiological measures, the HR is the more common to assess user's experience in a VE (Figure 2-9 shows the typical response of an HR measurement device). This vital sign has two different approaches: on the one hand, the HR itself is measured relative to the baseline initially established, attempting to contrast both risings and drops of the signal with the virtual events occurring in the virtual scenario [197] [203]. On the other hand, the Heart Rate Variability (HRV) measures the timeframes between two consecutive heartbeats. This measure provides a secondary HR response, which occasionally provides more information than the typical HR about the progress of users' status throughout the experience [196] [205].

Both HR measures are employed to carry out comparisons with the subjective assessments provided by the questionnaires, although it also exists a likelihood that comparisons do not generate rewarding results [197] [206] [207]. There are plenty of studies which attain relevant relations between the HR and the results of the evaluation questionnaires for presence, realism or immersion. Even though the heart rate variability varies to a greater extent when measuring these three parameters. In this manner, the studies which reveal satisfactory correlations support the initial belief that the HR and its variability are helpful assessment methods for VR systems [208] [209] [210].

Not only does the HR relates the three initial subjective concepts, but there are bountiful studies which analyse the changes on the signal relative to other concepts such as the anxiety or the workload. There is a clear and strong relationship between HR responses and subjective perception of anxiety, attributing the variations to this factor instead of the sense of presence or the immersion in most of the cases [197] [204] [210]. Furthermore, there is a linear relationship between the workload and HR responses, so an increase in the workload may imply, in turn, an increase on the HR in some cases [211] [212].

Figure 2-9. Common HR response during a virtual experience. The values must be normalised to establish proper comparison between all participants and conditions [204].

Similar to the HR, another measurement method is the SC, also known as the Galvanic Skin Response (GSR), which also serves to determine the users' status during virtual experiences [196] [199] (Figure 2-10 shows the typical response of an SC measurement device). The SC consists of two electrodes attached to the skin (usually in the thumb and index fingers) which measure variations on the skin sweating, converting them into an electrical signal. The signal is then analysed to determine how the users react regarding specific events which take place during the experience [213]. The SC measurement may also be split up into the general response and the Skin Conductance Variability (SCV) (the differences between them are similar to the case of HR) [211].

Some studies using both the HR and the SC, showing some cases wherein the SC provides better responses than the HR, although most of them show negligible variations between them [199] [214]. Therefore, the SC and the HR are both reliable measures to assess VEs and to compare with the subjective measures of presence, immersion or realism [138] [196] [215]. There are studies which legitimate this assumption since they prove the existence of correlations between both measures and the subjective responses obtained from subjective questionnaires [209]. Furthermore, the workload is a noteworthy indicator of similarities between them, since the SC also undergoes variations according to the workload which a user bears during virtual experiences [200].

According to the literature, there are two possible additional measures to assess the user's experience in VEs. On the one hand, the skin temperature, although it does not usually bear significant variations throughout whichever experience and if so, the responses are weak and

Figure 2-10. Common SC normalized response during a virtual experience. The solid line at 1.5 is a reference of common user’s condition, and the variable line depicts the variations of SC during a specific period of time [199].

slow, but the resulting curves are akin to the HR curves. There are no substantial grounds to make use of this measure instead of the HR or the SC [199] [200] [216]. On the other hand, the breathing frequency is only helpful when the experience demands physical work since otherwise the response is smooth and the assessment is not relevant [200] [212].

The events during a virtual experience are not the only factors which affect the physiological measures, but there is a significant difference whether the interactions are active or passive. Both the HR and the SC have higher responses when the user can actively and freely interact with the environment, either modifying it or solely touching or exploring. Contrarily, the passive interactions might also produce significant responses, but they are less remarkable than the active ones [199] [217].

Those interactions, both active and passive, may enhance when utilising haptic devices, which may unleash more striking variations in physiological measures [138] [213]. Nevertheless, although some studies stand up for the increase of responses owing to use haptic devices [216], there are not enough researches to reach reasonable conclusions about the sway of haptic feedback in these measures [218].

Autonomous Responses

Despite the inarguable helpfulness of the physiological responses, there are some additional objective methods to assess this kind of experiences. When users experience a reaction to an event or an incident in the scenario, its body cannot handle the autonomous responses of its nervous system. Hence, it is suitable to analyse the postural behaviour or the immediate physical responses since they probably shift depending on the visual, auditory or haptic feedback.

There are research lines which propose the measurement of aspects relative to au-

tonomous responses. On the one hand, the swift responses occur when an event takes place in the VE; there are reflex reactions or sharp body movements that indicate the user has experienced a remarkable event. On the other hand, the dominant body posture provides valuable information since the poses are unconscious as well as the likely changes during the experience. It is feasible to contrast both aspects with the subjective responses obtained with the evaluation questionnaires, seeking correlations between the answers and the autonomous users' reactions [204] [219].

Aftereffects

The last objective method to figure out the users' status is the appearance of aftereffects; that is, detrimental effects that the virtual experience is prone to generate on users. These effects are usually associated with uneasy phenomena such as sickness, drowsiness or fatigue owing to a lack of adaptation to the VE. They are also likely linkable with low levels of realism or immersion, or even a loss of presence.

The appearance of aftereffects may spoil a virtual experience; hence, it is mandatory to figure out whether users have felt some of these sensations during the experience. If this is the case, the rest of the assessments should be thoroughly analysed to determine likely biases. Likewise, the aftereffects must be compared with the subjective responses from questionnaires to determine likely relations. Even so, these phenomena are not common since most users can overcome the effects after an adaptation period to the VR system [220].

Chapter 3

Design of a Haptic Vest with Vibrotactile, Thermal, and Impact Feedback

The first step of this thesis is the development and design of an innovative haptic device. This new device must include diverse kinds of actuation to achieve optimal haptic feedback over the torso (front and back); thus, the most convenient option is the creation of a vest. The design must encompass the last advances in haptic technology since most of the devices are outdated. Those obsolete systems typically only include one kind of feedback over users, and its usage along with a VE becomes more complicated due to they cannot render stimuli coming from the scenario appropriately.

The haptic vest must ensure that whichever stimulus stemming from the virtual scenario is readily detectable by the user who is wearing the device. Hence, the first section of this chapter states some design considerations (e.g. the configuration of actuation systems or the textile design) to bear in mind in order to get the utmost device reliability.

The common objective of a VE is to get the uppermost similarity to a real environment, usually rendering two kinds of stimuli: visual and auditory. The visual feedback provides more quantity of information than any other stimulus, and it may be enough to reach high levels of realism. The auditory feedback is a great information source as well, but it is not always entirely needed. However, users habitually refer to an improved subjective perception when they hear the environmental noise [142] [221]. This fact suggests that more senses such as the touch, the taste or the smell might also be profitable to enhance the user's experience in VEs. However, the taste and the smell are chemical senses, so it is practically impossible a faithful simulation with the ongoing technology advances. Conversely, the simulation of touch is readily attainable since haptic devices are the order of the day, providing the ability either to explore a VE actively or to perceive touch sensations passively over any body area.

The vest is initially conceived as a tool to improve user’s experience through strengthening the subjective perception in VR systems. In this case, the vest mainly focuses on enhancing serious games for training and learning. The vest may be helpful because it allows users to receive passive stimuli via the skin, becoming haptic feedback an outstanding supplement for visual and auditory stimuli. Thereby, users receive additional feedback, approaching the whole system to reality, which might evolve into an enhanced ability to interact with whichever virtual object, element or avatar in the environment.

The actuation methods must be cautiously selected to accomplish the best simulation of each virtual event, considering several aspects such as the capability of creating realistic stimulations related to events in the VE, the capability of integrating the actuators in the vest or the easiness to control and power all the required actuators concurrently. Analysing those aspects leads to the selection of vibrotactile, thermal, and impact systems to generate multimodal haptic feedback.

It is also crucial to consider the control of the complete system, which must be subdivided to achieve the appropriate management of the haptic vest operation. The next sections show a detailed explanation of the objectives of the vest’s control, the subdivisions to control each actuator individually, and the overall control which communicates and receives instructions from the VR system so that the haptic vest renders the corresponding feedback.

3.1 Design Objectives

The development must fulfil some requisites and specifications indispensably in order to achieve the best design of the haptic vest. These specifications are related to the stimulation modes and the required control to adequately render the stimuli, the positioning of actuators over the vest, or the textile design so that users can adequately notice every stimulus.

The required haptic feedback strongly hinges on the VE to which the vest is initially focused since the stimuli vary regarding the scenario at issue. The original VE aims to train first responders developing menacing scenarios wherein users have to carry out diverse tasks to avoid risk situations or fatal consequences after a terrorist attack. Nonetheless, the vest can also be used with any VE, even though haptic stimuli might require modifications in order to adapt the vest to the needs of the correspondent application. The selected modes must create helpful stimuli so that users can notice indications, contacts with environmental elements or events taking place during those situations.

The most important mode is vibrotactile stimulation since it is useful to create stimuli which simulate interactions with elements or contacts inside the scenario, for instance, a blow with an avatar or a wall, or a deliberate contact from an avatar on the user’s shoulder to give an indication. The thermal stimulation allows simulating the environmental temperature depending on the cold or warmth in the scenario as well as to simulate the closeness to

particular thermal spots. Lastly, considering that the haptic vest gears towards the training of first responders during threatening situations, the impact feedback is essential to simulate sudden events, such as bullet shots or the shrapnel of a nearby explosion, among others.

After defining the modes of haptic feedback and their corresponding purposes, the next step is to select the proper actuators to create the stimuli and determine how to adapt them to the textile design of the vest.

Another critical aspect to consider is the control of the complete system, attempting that the generated stimuli are congruent among them, synchronising visual, auditory and haptic events stemming from the VE. The vest requires a control system with a two-fold objective: on the one hand, an individualised control of each actuator in order to ensure the proper configuration of haptic sequences; on the other hand, the system must be linked to the VR system which manages the signals coming from the scenario to accomplish the vest operation with minimum delays. This control systems thus allow the vest to render all stimuli (visual, auditory and haptic) simultaneously, enhancing the quality of the system, and seeking to improve the sense of presence and the immersion of users in the virtual scenario.

Nevertheless, the design is not utterly related to technical aspects of the haptic vest, but the psychophysical features of perception in the torso are remarkable aspects to determine how to place the actuators over the garment. The values of spatial acuity serve to precisely distribute the actuators so that users can notice and understand the information of haptic patterns. Moreover, the placement method has to assure the actuators are steadily attached to the skin, aiming users can reliably perceive all haptic stimuli.

The textile design must be flexible and adjustable so that users can readily wear the vest. It is unfeasible to create a unique, adaptable vest which fits all sizes; thus, the best alternative is to create several vests for different ranges (S-M, L-XL). However, different sizes might entail changes in the number of actuators owing to the space constraints in the smallest vests. Therefore, the minimisation of all elements (actuators and driver systems) has vital importance to accomplish the best design of the haptic vest.

The next sections present the selection procedures of all actuators, the control systems for each kind of stimulation, and the design of innovative actuators if required. Additionally, the overall control system is exhaustively explained to understand how the whole system works, from the virtual scenario stems a signal until the user perceives a haptic stimulus. Ultimately, the textile design is exposed, focusing on the fabric selection, the analysis about sizes and the disposal of actuators over the inner of the vest.

3.2 Vibrotactile Feedback

A virtual scenario seeks to recreate a place as realistically as possible by accurately simulating the scenario geometry, the lighting, or the avatar behaviour, among other features. However,

the main objective is to simulate events or behaviours that are difficult to reproduce in reality, even when they may be useful for users. If the scenario is sufficiently realistic, and users perceive contacts and events via the sense of touch, they are capable of carrying out the commended tasks and accomplish the initial objectives. Thus, including vibrotactile feedback provides a versatile actuation method in order to simulate plenty of the possible interactions in a VE.

The first step is to determine the more appropriate method to render vibrotactile stimuli. During the selection, not only is it needed to pay attention to the technical features of the actuators, but there are other key characteristics such as the feasibility of integration in a vest, the power requirements, or the comfortability for users. It is then required a thorough analysis of available methods, selecting the most adequate for this specific device.

After selecting vibrotactile actuators, it is necessary to define a driver system for handling those actuators in order to ensure accurate functioning. The objective is to manage the supply times, or the operating power at every moment, pursuing to generate sequences so as to create haptic patterns which users easily identify as specific stimuli provided by the virtual scenario.

3.2.1 Methods of Actuation

The selection procedure reveals that vibration motors are the best option to create vibrotactile feedback instead of other alternatives such as pneumatic systems, hydraulic systems, or Electrical Muscle Stimulation (EMS). The most important feature is related to the size since motors are generally small, which implies a straightforward integration into any fabric besides the possibility of integrating a large number of actuators. This fact implies, in turn, a higher capability of creating more sophisticated patterns, broadening out the number of stimuli displayable over users wearing the vest. Even so, the distribution and the precise quantity of actuators are still unknown since both aspects depend on the vibrotactile spatial acuity on the torso (see Chapter 4).

The control of vibration motors is straightforward since it only requires a simple and small driver circuit, which allows for adding numerous motors and drivers without lessening wearability. The driver circuit does not need high voltages or currents to operate; hence, there are no risks during the usage, and the power supply systems may be small. Lastly, the operating range of motors is inside the perception range of vibrations in the skin, so it is possible to create a vast catalogue of vibrotactile patterns which are readily perceivable.

The definitive selection is the consequence of an extensive study about different methods of actuation, dismissing two approaches:

- Electrical Muscle Stimulation (EMS) is a method which activates the muscles through stimulating the nerves with an electrical signal [222]. This system produces muscle

Figure 3-1. EMS system in which electrodes are placed over the arms. If the user touches something, low electrical currents flow through the electrodes and create different stimuli depending on the intended sensation [226].

contractions that users might identify as tingles, blows or forces according to the intensity of the signal in diverse applications such as training or rehabilitation [222] [223] (see Figure 3-1).

The EMS fulfils some requisites of the desired tactile system for the haptic vest such as the small size of the actuation system (it is composed of thin electrodes and cables) that eases its integration into the vest [222]. However, there are some disadvantages which lead to dismissing this method: 1) the EMS requires a complex driver circuit to properly display the stimuli over users' skin, which hinders the placement of the hardware over the vest, being even necessary a driver system external to the vest to manage the whole system; 2) the EMS requires calibration since each user can bear a different stimuli intensity, complicating the generalisation of feedback; 3) the EMS requires direct contact with the skin which may entail comfortability problems or ethical issues, hindering the widespread usage of the device.

- Pneumatic or hydraulic systems. They are systems which would ease the creation of pressure stimuli utilising bladders with shifting levels of air, creating realistic sensations since most of the contacts through the touch are akin to pressure changes over the skin. Nevertheless, those devices require pipes in order to distribute the air or the liquid over the vest as well as a compressor which is usually bulky and noisy, avoiding a comfortable and prolonged usage of the haptic vest [224] [225].

3.2.2 Selection of the Actuator

The next issue to confront is the selection of the most appropriate motor to create intended vibrotactile stimuli. The tested motors are provided by Precision Microdrives (Precision

Figure 3-2. A coin motor (left image) and an LRA (right image). Both types of motors are discarded since they do not offer the sought features for the integration into the haptic vest (Precision Microdrives Ltd., London, England - www.precisionmicrodrives.com).

Microdrives Ltd., London, England - www.precisionmicrodrives.com). It is required to consult the manufacturer guides up and cautiously study the motors' parameters to select the actuator which best fits for the requirements of the haptic vest.

There are three likely types of motors for its embedment in a haptic vest. The Eccentric Rotating Mass (ERM) motors are direct current motors with a cylindrical shape. The vibration is caused by an offset mass attached to the shaft: when the shaft rotates, the mass creates an asymmetrical centripetal force which, in turn, produces a net centrifugal force that displaces the motor. This continuous displacement of the motor creates a vibration [227].

The coin motors are compact actuators with coin shape (see Figure 3-2). They are ERM motors, but the rotation of the eccentric mass is due to a magnetic field created between two voice coils and a neodymium magnet. The main difference between cylindrical ERM motors and the coin motors usually lies in the start voltage, which is considerably more significant in the case of coin motors. Furthermore, there are differences in the range of displayable vibrations by both motors that must be borne in mind to select the proper actuators [227].

The last type is the Linear Resonant Actuator (LRA) which is significantly different from the two previous types since they do not use a rotating mass to create the vibration (see Figure 3-2). In this case, the system is composed of a spring, a moving mass, a magnet, and a voice coil. The magnet creates a magnetic field, and the coil causes the movement of the mass which, in turn, returns to its original position employing the spring. The fast and constant repetition of this effect generates vibration.

Even though the features of motors' operation are essential to select the vibrotactile actuator, there are some criteria related to both shape and technical characteristics. There are four factors, namely: dimensions, encapsulation, vibration intensity (related to frequency and amplitude), and control easiness.

The first preliminary approach consists of analysing the three types of motors. The main advantage of LRAs is their great flexibility to handle the operating parameters since it is possible to vary the frequency and the amplitude separately. However, the intensity of vibrations of LRAs is not enough to accomplish a proper perception of stimuli on body areas with poor sensitivity (they only reach up to *175 Hz* and *1.5 g*). Moreover, they need a supply of 2 V, which demands additional power stages to achieve the proper operation of these actuators. Both the intensity and the necessity of low voltages to operate are the main reasons to discard LRAs. They singularly focus on applications for hands, tactile screens, and, in conclusion, areas with greater sensitivity. Moreover, the control of LRAs is markedly more intricate since it requires complex and large driver circuits; thus a high number of actuators would require large areas to place the driver systems and the consequent loss of wearability [228].

This approach also serves to test the chief differences between ERMs and coin motors. According to the manufacturer datasheets, the coin motors customarily display vibrations of lower intensities than an ERM motor, although vibrations may be intense enough to stimulate areas such as the torso. Even so, ERM motors have a broad range of displayable vibrations (they can reach higher frequencies and amplitudes than the rest of analysed actuators), which entails a greater versatility to create haptic patterns. Thence, the final resolution after the study is the usage of ERM motors.

The second approach consists of testing several ERM motors with different operating features in order to determine the best option according to the previously established criteria. The control easiness does not influence the decision since the driver circuit is similar for all ERM motors. The dimensions are the critical aspect to consider, particularly the diameter since it may be a motive for discomfort due to motors are tight between the fabric and the skin. Conversely, the length of motors is fairly small, and it does not overly affect their integration into the vest. In such a manner, motors with diameters larger than *8 mm* are discarded, which entails that remaining available motors have lengths inferior to *20 mm*.

The encapsulation is the last criterium to analyse. All motors require the housing to accomplish a proper motor operation when the actuator is attached to the fabric; otherwise, the motor can barely operate since the rotating mass is continuously blocked and the actuator does not generate the vibration correctly. It is hence preferable to select a factory encapsulated motor to avoid the creation of housings for free ERM motors.

After studying all the essential aspects in the second approach, the selected motor is the model 304-116 (Precision Microdrives Ltd., London, England - www.precisionmicrodrives.com): an encapsulated motor whose diameter is *5.3 mm*, and its length is *20.1 mm* (see Figure 3-3). The rest of the technical features (both operative and electrical) are thoroughly detailed in the next section.

Figure 3-3. The selected vibration motor is an ERM motor: model 314-116 from Precision Microdrives (Precision Microdrives Ltd., London, England). This actuator fulfils the requisites for the integration into a haptic vest regarding its size, voltage, and vibration intensities.

3.2.3 Features of the Selected Motor

The operating features of the motors are essential to define the driver circuit for handling the actuators. Those features are voltage, current, speed, vibration frequency, and vibration amplitude. It is necessary to set forth their particularities to deal with them during the operation in order to exploit the full potential of motors.

According to the datasheet, the rated operating voltage of the selected model is 3 V which indicates the typical point of operation. The datasheet points out a maximum operating voltage of 3.6 V , denoting that higher voltages might imply unpredictable motor operation. The minimum operating voltage is 1 V , corresponding to the needed voltage to get a motor vibration. Nevertheless, the motors can be powered with voltages up to 5 V according to conducted tests, and they also can be maintained at those voltages during prolonged periods without damages or malfunctioning.

The current is a feature entirely dependent on the voltage since the operating current linearly varies in keeping with the operating voltage. Despite the linearity, the rated current provided by the datasheet (44 mA) is an approximate value because it depends on many variables and is hardly controllable. This parameter must be considered to configure the driver circuit of the motor since all components must be able to bear those currents or slightly superior values to ensure the operation without troubles.

The rotation speed is firmly related to the voltage as well. Although the motor has a rated vibration speed of 16.700 r.p.m. , the datasheet indicates likely variations up to 3.000 r.p.m. according to diverse circumstances. Thus the speed is neither an adequate value to define the operating point due to the scarce accuracy of the real speed during the usual functioning. Hence, the speed and current are discarded, and the rest of the analysis is

performed only considering the voltage.

The vibration frequency and the vibration amplitude deserve particular emphasis since they are the most critical parameters to relate motor operation to haptic perception. The relationship between both variables has a unique role in knowing the motors' singularities when they are attached to the vest.

The vibration frequency is strictly related to the motor rotation speed since it is defined as the number of revolutions per second (see equation 3.1). In this manner, just as the rotation speed, the frequency is proportional to the voltage as well. Figure 3-4 (red line) shows the relation between the frequency (values comprised between *120* and *285 Hz*) and the voltage (values comprised between *0* and *3.6 V*) in accordance with the maximum values set out by the datasheet. Since the motor can operate up to *5 V*, it is necessary to carry out a characterisation to determine the corresponding frequency values for the remainder voltage range (*3.6 - 5 V*) [229].

$$f_{vibration}(Hz) = \frac{r.p.m}{60} = r.p.s. \quad (3.1)$$

The vibration amplitude is the range of the movement reached by a motor while is vibrating. The datasheet reports normalised values of the amplitude, taking as a reference to the movement performed by a mass of *100 g*. The amplitude is associated with the acceleration from gravity (*g*), although it would be possible to express in millimetres. However, the motor displacement is also affected by the frequency, and the values might be distorted [230]. In this motor, the amplitude is proportional to the voltage according to the graph, which shows values comprised between *0.2* and *1.45 g* (see green line in Figure 3-4).

The two prior explanations show undeniable evidence of a relation between amplitude, frequency, and voltage. Therefore, both frequency and amplitude are adequate to characterise the motors' operation, but it is needed a further discussion to evince the most appropriate parameter.

ERM motors only allow monitoring the voltage input between their terminals. The motors have a single controllable feature (the voltage); thus, a change of voltage unleashes a variation of both frequency and amplitude since they are interlinked [48] [231]. Each vibration depends on a combination of amplitude and frequency, and both parameters are valid to characterise the perception of vibrotactile stimuli [232] [233]. Therefore, the characterisation determines the curves of frequency and amplitude to know the operation of these ERM motors accurately.

Two additional features may affect the perception of vibrotactile stimuli: the rise time (i.e. time from a motor starts to vibrate until it reaches 50 % of the vibration amplitude), and the drop time (i.e. time from the power interrupts until the motor stops). Values of amplitude and frequency are highly variable during those times and, although the datasheet provides these times for the rated voltage, the measurement is needed to ascertain those

Figure 3-4. Main operating features of the selected ERM motor (model 314-116). It shows the evolution, according to the voltage, of vibration amplitude (blue line), vibration frequency (red line), the current through the motor (light green line), and the efficiency (dark green line) (Precision Microdrives Ltd., London, England - www.precisionmicrodrives.com).

values in the entire vibratory range (see Figure 3-5).

Drop times barely differ in the entire range, but rise times are rather high when they must reach low intensities (i.e. low amplitudes and frequencies). The duration of all stimuli with vibration motors must be long enough (above 100 milliseconds) to guarantee that users notice target vibrations without mistake.

There are two required additional actions to manage the vibrotactile actuators rightly: to create a driver circuit to handle the operation accurately (see Annex A) and to characterise the motors in order to get the entire voltage-frequency during the typical operation of motors in the haptic vest.

3.2.4 Characterization of the Motor

As pointed out above, the datasheet indicates a maximum operating voltage of 3.6 V, but the preliminary tests have proven that motors can handily operate with higher voltages. Therefore, the selected vibration motor needs a characterisation in order to determine the operating curve up to 5 V (i.e. the maximum voltage provided by the power supply). The datasheet also indicates that the minimum voltage to operate the motors is approximately 1 V, which is a value that must be validated as well.

Each vibration motor requires an electronic driver circuit to regulate the voltage applied among the terminals of the motor at every moment. The circuit controls the vibratory frequency and amplitude since both parameters depend on the voltage input. The design of

Figure 3-5. Rise and drop times of the '304-116' motor in its entire operation range (steady-state).

the driver circuit appears in Annex A.

The original performance curve shows the behaviour of the vibration motor under certain experimental conditions which are only known by the manufacturer. The datasheet values may not be applicable since the conditions bore by the motors over the vest are, probably, highly dissimilar. It is hence befitting to perform a characterisation covering the complete range of voltages that the power supply can provide to the driver circuit (0 to 5 V) in order to know the relationship between the temporal frequency, the amplitude and the voltage, and achieve the utmost efficiency of vibration motors.

Before starting the characterisation, it is needed to obtain the equivalences between the PWM value provided by the controller and the voltage values by directly measuring between terminals of the motor using a digital multimeter. Afterwards, the operating curve of temporal frequency is determined with strict experimental conditions, increasing the voltage from 0 to 5 V by steps of 0.05 V using the PWM-voltage relation previously obtained. The setup registers the signal, which is processed to erase the ambient noise by filtering. It is then applied a Fourier transform in order to get the dominant frequency (i.e. the frequency where the amplitude spectrum has a maximum) of each vibration which, in turn, corresponds to the vibration frequency for each voltage (Figure 3-6 depicts the amplitude spectrum and the dominant frequency of a specific vibration).

Figure 3-6. The spectrogram shows the measurements of frequency and amplitude obtained by using a measurement device. The yellow crest depicts the dominant frequency around 200 Hz , and the amplitude is 0.7524 g in this case.

There are diverse measurement instruments to conduct the characterisation. The first device is an accelerometer (ADXL337 - Sparkfun, Boulder, USA) whose factory settings allow measuring the dynamic acceleration caused by vibration motors between 0 and 500 Hz (see Figure 3-7). This range is enough to carry out the measures of the vibration motors since the maximum frequency in the datasheet is 290 Hz . The accelerometer needs a capacitor of $0.1\text{ }\mu\text{F}$ placed between the power supply and ground to remove the noise during the procedure.

The accelerometer may adversely affect the measurement procedure since it must be attached to the vibration motor; thus, the vibration might be distorted, and the obtained values could not correspond to the real frequency and amplitude values during the ordinary operation. An alternative measurement device is an omnidirectional electret microphone (see Figure 3-7) which can be placed at small distances from the motor to obtain the vibration frequency and amplitude. The main advantage is the sampling frequency of the microphone, which is about 44.100 Hz (considerably larger than 500 Hz of the accelerometer). The microphone needs additional components to build a pre-amplification stage to appropriately acquire the data, consisting of a capacitor ($1\text{ }\mu\text{F}$) and a resistor ($2.2\text{ k}\Omega$).

The data acquisition procedure is performed using Arduino (Arduino UNO - Arduino, Italy) to control the power supply voltage of the motor through PWM, and MATLAB/Simulink (The Mathworks, Inc. - Natick, USA) to process and analyse the data. The control board uses a Pulse-Width Modulation (PWM) output to power the motor between 0 and 5 V through a power stage to protect the motor against either overcurrent or overvoltage states.

Results of both acquisition methods are nearly equal, but those of the omnidirectional microphone are used to get the frequency values, and those of the accelerometer to get the vibration amplitude. Frequency results of the accelerometer are dismissed because the nar-

Figure 3-7. The methods to characterise the vibration motor are an accelometer embedded in a small PCB with the required electronical components for its operation (left image) (Analog Devices, Inc., Massachussets, USA - www.analog.com), and an omnidirectional microphone which only needs a connection with a data acquisition board (right image) (RS Components, Corby, UK - uk.rs-online.com).

row bandwidth leads to the saturation of the device when measuring the highest intensities of vibration motors (between 280 and 330 Hz).

The characterisation employs four different conditions to analyse the real capability of vibration motors (condition (a) in Figure 3-8), and the dissimilarities between three likely attachment modes to the vest (conditions (b), (c) and (d) in Figure 3-8). In all cases, the motor is hung up in a bracket, although attached to a fabric or a 3D support in the three last conditions to emulate the actual situation during the haptic vest's operation.

The first scenario consists of a free motor without contact with other objects or materials. The objective is to know the full capabilities of the motor, which is helpful to establish a reference for analysing the motor operation in the rest of the scenarios. The second scenario consists of the motor fitted in a customised frame which is designed to attach the motor in the vest without directly sewing the actuator to the fabric. Thereby, the curve exhibits the differences between the free motor and the motor fitted in the frame.

The third scenario consists of the motor directly sewn on the vest's fabric; whereas the fourth scenario consists of the motor fitted in the frame which, in turn, is sewn to a piece of the vest's fabric (i.e. similar conditions to the real vest's operation). Both scenarios represent the two easiest options to attach the motors to the vest, aiming to elucidate the best manner to place the motors, either sewing the motor or using the customised frame.

After comparing both devices, the curves are somewhat similar, and there only are noticeable differences in some specific measures, even though the entire curve always follows the same tendency. The subsequently presented results refer to the data obtained using the microphone due to its higher sampling frequency which provides a broader measurement range.

Each scenario results in a curve relating the supply voltage with the vibration frequency (see Figure 3-9). The comparison among the curves shows the particularities of each scenario:

Figure 3-8. The image shows the materials for the data gathering in four conditions. The condition (a) consists of the free motor. The motor is sewn to the fabric in the condition (b); attached to the 3D frame in (c); and attached to the frame, which is sewn to the fabric in (d).

Figure 3-9. Curves corresponding to the four conditions in Figure 3-8. The red plot corresponds to the condition (a), the blue plot to the condition (c), the green plot to the condition (d), and the last plot corresponds to the condition (b).

if the motor does not have restrictions (i.e. the free motor and the motor with the frame), the values of frequency and amplitude are considerably higher than the values of the datasheet (the range is comprised between 55 and 470 Hz); whereas attaching the motor to a fabric entails disparities at frequencies as of 150 Hz, approximately, and the resulting ranges of frequencies are comprised between 60 and 330 Hz.

Either way, those scenarios show the manufacturer imposes substantial restrictions which forcefully limit the motor vibration. The two first scenarios provide a general idea about the real capabilities of the motor as well as the consequences of the applied restrictions (red and blue lines in Figure 3-9).

Conversely, the results of the two last conditions exhibit a clear divergent tendency since the values of frequency and amplitude reached by the motors are considerably lower. The vibration intensity mitigates when motors are attached to the fabric, although there are differences between both scenarios: on the one hand, the low frequencies in the third scenario are probably due to the high pressure of the seams which fix the motor to the cloth; on the other hand, the fourth scenario shows that the frame alleviates the pressure and the motor reaches higher frequencies, which are more similar to values of the manufacturer curve. Therefore, the motor-frame configuration is the most adequate because the mitigation is weaker as regards the motor sewn over the fabric directly (see condition (d) in Figure 3-8

Figure 3-10. Characterised frequency (red line) and amplitude (blue line) curves, and original frequency (dark yellow line) and amplitude (green line) curves. The blue line corresponds to the (d) scenario in Figure 3-8. There is a clear relation between frequency and amplitude curves, even though there are differences between characterised and manufacturer curves due to the conditions during the data gathering.

and green line in Figure 3-9).

The selected characterisation curve shows that motors begin to operate at 0.5 V instead of 1 V as the manufacturer curve indicates (see Figure 3-10). The new curves depict the voltage-frequency-amplitude relation between 0.5 and 5 V , which is a clear benefit in order to create haptic stimuli since the new range is more extensive than the original. The results also show a strong dependence on the operating conditions, so any change (fabric or support, among others) would require a new characterisation.

Figure 3-10 also depicts the characterised amplitude (blue line) as of the values obtained with the accelerometer. In this case, the new vibration amplitudes differ between 0.25 g (0.5 V) and 1.46 g (5 V).

Manufacturer and characterisation curves show linear relationships between frequency, amplitude, and voltage, and changes in voltage imply proportional variations in frequency and amplitude. Therefore, it is feasible to set two fourth-degree equations to obtain the frequency (3.2) and the amplitude (3.3) for each supply voltage in these experimental conditions. Furthermore, a three-degree equation relates frequency and amplitude (3.4) (see

Figure 3-11. Amplitude (g) as a function of the temporal frequency (Hz) of '304-116' motors. They begin to vibrate at 0.51 V (i.e. 63 Hz and 0.219 g), and each point of the curve corresponds to a specific supply voltage.

Figure 3-11). The three equations are adjusted by using polynomial regression and the characterisation data.

Henceforth, the subsequent experiments about vibrotactile perception employ the frequency, easy to perform comparisons with other motors or the same ERM motors in other experimental conditions. Nonetheless, the perception does not only differ owing to the variations in frequency but the utter vibration composed of a particular amplitude and frequency. All results can be given in terms of the combination of frequency and amplitude by using 3.4.

$$F(Hz) = -0.657V^4 + 9.204V^3 - 45.99V^2 + 147.5V - \quad (3.2)$$

$$A(g) = 0.0022V^4 - 0.028V^3 + 0.0114V^2 + 0.085V + 0.15 \quad (3.3)$$

$$A(g) = -6.72 \Delta 10^{-8} F^3 + 4.1 \Delta 10^{-5} F^2 - 0.031F + 0.27 \quad (3.4)$$

3.3 Thermal Feedback

The temperature is a stimulus that any person continuously notices in daily life. Hence, an aspect that must be expediently simulated using thermal actuators to emulate a significantly realistic VE. A thermal feedback system serves to simulate diverse virtual events such as the heat stemming from a nearby fire, or the cold during a snowstorm. In the light of the undeniable advantages, the objective is to determine the more appropriate thermal actuator to display sensations of both heat and cold realistically.

There are several available devices to render haptic stimuli handily, but the selection must deem some requirements related to the specific applications of the haptic vest to guarantee users notice the temperature variations accurately. It is then necessary a thorough analysis of the features of each device in the same manner of the vibrotactile actuation analysis.

The thermal actuator also needs a driver circuit to accomplish a reliable operation. The control must ensure the temperature displayed over users does not overstep the perception limits of thermoreceptors ($15\text{-}45^\circ\text{C}$), avoiding the activation of nociceptors and the resulting painful sensations.

3.3.1 Methods of Actuation

Unlike vibrotactile stimulation technologies, devices able to simulate thermal sensations are scarce. Peltier cells are the most common method since they are small and easy to integrate into haptic devices, even though there are other options such as elements made of Phase-Change Materials (PCM), or heating resistances.

Peltier cells fulfil most of the demanded requisites to integrate a thermal actuator into a haptic vest regarding the size and the thermal features. On the one hand, the cells are thin elements, which eases the integration and avoid excessive bulkiness. There are diverse available sizes (from a few millimetres to several centimetres) with similar operating features, being possible to select the most appropriate cells according to the specific requirements. On the other hand, almost every Peltier cell can reach temperatures between 0 and 100°C which make them suitable for this specific application since that range far exceed the temperature limits that activate the skin's thermoreceptors.

The main drawback of Peltier cells is the complexity of the driver circuit to control the temperature displayed over users. It is needed a thermal sensor to close the control loop and to achieve a smooth adjustment of the temperature, always avoiding the activation of nociceptors. The other remaining difficulty is related to the heat excess during ordinary operation, which may further cause unwanted heating, requiring a dissipation element to avoid this effect. Despite those particularities, Peltier cells are still an adequate device to render heat and cold stimuli using a haptic device.

Another method to display temperature stimuli is related to devices made up of PCMs.

These materials have the capability of storing thermal energy which may be released over users, displaying heat or cold stimuli. The working principle is a change of phase between solid and liquid states that generates a temperature gradient. The main advantage is the possibility to customise the shape, which allows the creation of small devices suitable for the embedment in the vest due to the high adaptability of PCMs. However, the devices need to be continuously heated or cooled by external means to store thermal energy, complicating the integration owing to the demand of an external cooling/heating system that must be attached to the vest [234].

The most intuitive manner to generate thermal sensations is the usage of a resistance, which only needs the flow of a current through it to create thermal variations. Nevertheless, that simplicity is also its primary drawback. That passing current solely can generate heating, not cooling; hence, this method does not sweep the required thermal range, and it is not viable for its integration into the haptic vest.

Therefore, Peltier cells are the more suitable actuation system to display thermal stimuli over the body through a haptic vest without remarkably increasing its weight, size or bulkiness. Next subsections expound the selection of the appropriate actuator and the actions required to alleviate the drawbacks.

3.3.2 Peltier Working Principle

Peltier cells are devices capable of displaying cooling and heating stimuli due to a thermal flow caused by the thermoelectric effect, which is strictly related to Peltier and Seebeck effects.

The Seebeck effect (see Figure 3-12) arises from the exposure of a metal junction to a temperature gradient which causes the heating on the top of the element, while the bottom is cooled. The phenomenon creates electron/hole pairs which absorb heat on the top; meanwhile, the pairs are recombined on the bottom, rejecting the heat and cooling that side. The flow of the pairs creates a current between both sides of the metal junction and, therefore, a voltage difference which is the base of Peltier effect [235] [236].

The Peltier effect is, somewhat, the inverse procedure of the Seebeck effect. The phenomenon (see Figure 3-12) consists of the pass of current between a junction of materials with different electrical properties such as metals or semiconductors. When a voltage is applied amid both sides of the junction, a flow of both electrons and holes begins to course between, on the one hand, a ceramic plate and the intermediate junction and, on the other hand, between that junction and the facing plate. In such a manner, the side whence the current departs gets cool, whereas the opposite side gets heat. If the voltage inverses, the current flows reversely, and the heat and cold sides also reverse [235] [236].

Peltier cells intend to create a Peltier effect. They are composed of two different semiconductors (n-type and p-type) alternately distributed besides electrically connected in series

Figure 3-12. Graphic explanations about Peltier and Seebeck effects. The Peltier effect consists of flowing electrons between N and P semiconductors owing to a voltage which creates the heating and the cooling of opposite sides of the Peltier cell [235].

and thermally in parallel. Two ceramic plates enclose the semiconductors, which also serve to transmit the thermal sensations originated as a result of the Peltier effect in the inner elements. In this manner, those plates are the means to render thermal stimuli over users. The cells have two cables connected to the semiconductor elements in order to apply the voltage that generates the Peltier effect and the resulting temperature gradient [236].

A typical operation of a Peltier cell begins when a voltage is applied between the cables of the thermal device, generating a current which passes through the semiconductors enclosed by the ceramic plates. In this manner, the ceramic plate where the electrons are flowing undergoes a cooling, whereas the plate where the electrons arrive, undergoes a heating.

3.3.3 Selection of the Actuator

The selection of the Peltier cell depends on their features, both dimensional and electrical, although there must be other concerns about the driver circuit or the heat sink to dissipate residual heat. It is then necessary to test several cells with different features in order to determine the most suitable actuators for this specific application. The driver circuit must be defined according to the selected thermal actuator afterwards.

Thereupon, the dimension and shape of the selected Peltier cells must be adequate to settle them in the vest. They have to fulfil some requisites regarding the dimensions: 1) easiness to affix them in the vest in order to prevent hindering the rest of elements in the device (vibrotactile or impact actuators); 2) small size to avoid hindrances during the natural movements of users. The best option is to employ square cells since the transmission of temperature over the skin is more uniform in contrast with the usage of alternate shapes (rectangular or customised forms). The maximum dimension must be *30 mm*, in such a manner that the vest can hold the required quantity to stimulate the torso optimally.

Four significant technical features must be explored in order to select the adequate actuator (see Table 3.1):

- Maximum temperature differential (ΔT_{max}). It is not very relevant since common values of this parameter are around *65 °C*, whereas the range of non-painful temperatures is comprised between *15* and *45 °C* (i.e. a difference of *30 °C*). Thus, any available Peltier cell can render temperatures of that range since the maximum difference is lower than common values of the differential.
- Supply voltage (V_+). The Peltier cells need a minimum power around *5 V* so that they can share the same supplying system that vibration motors.
- Current (I_p). The current passing through the Peltier cell must be low enough so that the controllers bear those currents and the driver circuit is not oversized.

Table 3.1
Features of the selected Peltier cell

Main feature of Peltier cell	Value
Maximum Temperature Differential	$\geq 66\text{ }^{\circ}\text{C}$
Supply Voltage	5.0 V
Current	8.4 A
Maximum Heat Pumping Capacity	24.0 W

- Maximum heat pumping capacity (Q). This value is a key parameter to select the proper Peltier cell since it reveals the quantity of heat to dissipate, and not overheat either the user's skin or the driver circuit. All suitable cells have capacities between 10 and 45 W , which are high values that can produce overheating. Hence, a heat sink ensures the safety of electrical components in the circuit and the constant maintenance of temperatures rendered by the cell.

The selected cell is the TES1-07150 model, which is manufactured by EverredTronics Ltd. (Shanghai, China) (see Figure 3-13 and its main features in Table 3.1). This model can display the entire range of non-painful stimuli since the maximum temperature differential is $66\text{ }^{\circ}\text{C}$ (the range is $15\text{-}45\text{ }^{\circ}\text{C}$). Even so, it is necessary to continuously oversee the temperature in the side of the cell placed over the skin, avoiding the generation of undesired thermal stimuli.

The maximum voltage is 8.4 V , although it is feasible to power the cell with lower voltages; the cell thus can be powered with the same supplying system used for the motors. The maximum current is 5 A which might eventually cause faults or malfunctioning during cells operation, so the driver circuit must be carefully designed to regulate the current passing through the Peltier cell at every instant. The design of the driver circuit appears in Annex A.

The heat pumping capacity of the selected cell is 24 W , reasserting the necessity of a heat sink to avoid overheating either the user's skin or the driver circuit. If the system does not include a heat sink, the temperatures on the side attached to the skin might reach values above $45\text{ }^{\circ}\text{C}$ which, in turn, might cause the activation of skin's nociceptors and the ensuing painful sensations. Moreover, the heat sink also prevents overheating derived from prolonged cold stimuli, which may cause continuous heating in the opposite side of the cell after long times, overheating the entire Peltier cell and creating counter-productive hot stimuli over the skin. The whole procedure to select the most appropriate heat sink appears in Annex A.

Figure 3-13. Model TES1-07150 of EverredTronics Ltd. This cell fulfils the requisites for its integration into the haptic vest regarding achievable temperatures, voltage, and current (EverredTronics Ltd., Shanghai, China - www.everredtronics.com).

3.3.4 Control of the Thermal Actuation System

Chapter 2, Subsection 2.1.2 stated a very limited range to render non-painful thermal stimuli. The temperature of a stimulus must never exceed 45°C , and it must not descend either below 15°C to avoid activating nociceptors of the somatosensory system.

A Peltier cell in the vest is, approximately, at the skin's temperature when it is not operating (around 32°C). A sudden thermal phenomena could trigger a rising of up to 13°C ($45 - 32^{\circ}\text{C}$) or a drop of up to 17°C to reach the limits ($32 - 15^{\circ}\text{C}$). The driver system based on a PID controller must handle that process and maintain the target temperature (always between 15 and 45°C) during the required time. There can be overshoots during the rising or dropping processes, and the cell could exceed the pain threshold. Thus, the control system is essential to manage those phenomena and guarantee an efficient but secure rendering of thermal stimuli over users.

The control system requires closing the loop in order to handle precisely the temperature in the side of the cell contacting the user. To this end, the actuation system includes a thermal sensor (Pt-100, Class B; RS Components, Corby, UK), whose driver circuit appear in Annex A. The sensor is placed on a corner of the Peltier cell, taking up the minimum space to minimise the loss of the contact surface between the cell and the skin.

PID Controller

The temperature sensor (Pt-100) closes the loop of the control system: the sensor measures the temperature in the side of the cell attached to the skin, then the system calculates the error as the difference between the target and the measured temperature and, finally, the

controller applies a correction in the PWM output to adjust the current passing through the Peltier cell.

Measurements of the thermal sensor depend on several parameters, such as the driver circuit and the length of connections, or the particular measurement conditions in the haptic vest. Thereby, the first step is to calibrate the sensor so that every measure during the operation of the vest reaches the utmost precision and Peltier cells always maintain the temperature within the non-painful range.

The selected controller is a PID (Proportional, Integrative, Derivative) which have been used in prior studies to handle the operation of Peltier cells. The PID controller provides excellent performance, and it is low-cost, simple, and robust [88] [118].

The controller has to limit the maximum output to prevent the Windup effect caused by the saturation of the actuator which, in turn, could generate wrong values and erratic behaviours of the system. Those errors could eventually cause non-linearity or lack of congruency between two consecutive values of the output. The PWM output applied to the driver circuit might differ extensively, unleashing unpredictable effects in the Peltier cell operation.

After defining the main features of the PID controller, it is necessary to set the constants of the system: K_p , K_i , and K_d (i.e. the three terms of a PID controller). The most common method to ascertain those values is the usage of Ziegler-Nichols tuning rules [237]. The rules employ a step response of the plant (the Peltier cell in this case) since they use variables obtained from the shape of the response. The tuning is only applicable if the response has S-shape because the rules use the delay time (L) (time from the beginning of the step input until the system responds), and the time constant (T) (time from the end of the delay until the system reaches the target temperature with an error of $\pm 5\%$). However, although the rules provide a good approximation of the values, a manual adjustment may enhance the operation of the controller and the performance of the thermal actuator.

There are differences between the cooling and heating processes of a Peltier cell. Therefore, the constants of the controller are not equal in both cases. A reason is the difference between the original and the target temperature. The cell might undergo rises up to $20\text{ }^{\circ}\text{C}$ during the heating (from $25\text{ }^{\circ}\text{C}$ to $45\text{ }^{\circ}\text{C}$), whereas the temperature might drop only $10\text{ }^{\circ}\text{C}$ during the cooling (from $25\text{ }^{\circ}\text{C}$ to $15\text{ }^{\circ}\text{C}$).

However, the main difference lies in the residual heat during both processes. On the one hand, a Peltier cell during heating have to reach the target temperature, and then the control system has to prevent overheating by moderately reducing the current passing through the cell. The system could even turn off the system to remove the current if the heating becomes excessive.

Contrarily, the control of the cooling process of a Peltier cell must avoid undesired heating because of heat transmission from the other side of the cell. The heat sink prevents

Figure 3-14. The green line shows the step response of the Peltier cell up to 37°C , showing that the cell is capable of reaching the target temperature, but it does not maintain the value during long times since the cell continues heating. The orange line shows the step response up to 17°C , showing the thermal system lasts around 40 seconds to reach the target temperature since there is a significant overshoot at the beginning.

the trouble for short periods after the beginning of the operation, but the control must activate after long periods by modifying the passing current to achieve overcooling and, hence, avoiding the influence of the residual heat coming from the other plate.

Figure 3-14 depicts the experimental step response for heating (up to 37°C) and a cooling case (up to 17°C). The distinctive values are $L = 1.2$, $T = 14$ for the heating case, and $L = 1.5$, $T = 11$ for the cooling case. The responses for both cases using the closed-loop system (see Figure 3-15), and the step response, are shown in Figure 3-16. The obtained values for both cases utilising Ziegler-Nichols rules shown in Table 3.2.

Peltier cells are usually rather slow: the step responses in Figure 3-14 show the cell reaches the hot set point ($\pm 5\%$ of error) after approximately 35 seconds; whereas the cell

Table 3.2
PID values using Ziegler-Nichols tuning rules.

	$K_p = 1.2 T/L$	$T_i = 2L$	$T_d = 0.5L$
Heating	14	2.4	0.6
Cooling	8.8	3.0	0.75

Figure 3-15. The control system is composed of the Peltier cell (the plant), and the PID controller which corrects the input to adjust the temperature value of the cell. The control is closed using a thermal sensor (Pt-100) which continuously monitor the temperature in the side of the Peltier, which is attached to the user's skin.

reaches the cold set point more swiftly (around 10 seconds), although the difference between the steady temperature and the setpoint is smaller. Either manner, those times must be shrunk to achieve proper synchronisation between visual, auditory, and haptic stimuli during the vest's operation.

Figure 3-16 shows the responses after the adjustment of the PID controller using the constants of Ziegler-Nichols rules. The plot for the heating case shows a relatively good response with appropriate behaviour in the stationary state, but it is excessively slow to reach the set point. The objective is thus to refine the constants empirically to reduce the rising time.

In contrast, the cooling plot shows a swift response (the cell takes around 10 seconds to reach the setpoint), but the empirical refinement must lessen the large overshoot to prevent troubles and pain during the operation.

The procedures to adjust the values given by the tuning rules are similar in both cases. Hence, it is thoroughly explained the adjustment of PID constants of the heating case, whereas the cooling case is only reported with the resulting plots.

The whole experimental procedure maintains a permanent setpoint fixed at 45 °C. The steady temperature is about 28-29 °C in all cases. It is unfeasible to set an initial fixed temperature due to continuous variations of ambient temperature in the course of the experiments.

The first step is to lessen the error in the stationary state through varying the integrative constant of the controller. K_i affects that error provided that external disturbances bring it about. However, a variation of K_i can originate large overshoots and, therefore, high temperatures on the side of the cell attached to the skin during the first instants of operation (users could even notice pain or unease sensations). Furthermore, the variation of K_i can also reduce the velocity of the whole system. It is thus demanded to attain a commitment

Figure 3-16. The upper line depicts the response of the Peltier cell under the influence of the PID controller for a heating case (45°C), showing a response with low stationary state error but somewhat slow. The other line shows the response of the Peltier cell in a cooling case (17°C), showing a fast response but with a remarkable overshoot that must be corrected to ensure the proper operation.

Figure 3-17. Four responses with different values of the integrative constant. The graphs corresponding to extreme values (1 and 2.4) show opposite behaviours as regards the overshoot, and both reach the stationary state after long times. The two graphs with intermediate values (1.9 and 2.05) show responses with small overshoots, reaching the stationary state in short periods (around 10 seconds).

between a restrained overshoot and a swift response, aiming the system reaches the target temperature at the shortest possible time with minimum overshoot.

Figure 3-17 shows the results of K_i variation. The lessening of the overshoot is quite clear, but responses are unavoidably slowed down (e.g. the time to reach the setpoint is about 40 seconds when the constant is 1.0). Nevertheless, the stationary state error remains roughly permanent in all cases. As a change of K_i does not imply a lessening of the error, but only affects the overshoot, an adequate response is obtained with $K_i = 1.9$, because the cell takes around 12 seconds to reach the setpoint and there is no overshoot.

The overshoot, the stationary state, and the velocity also hinge on the value of the proportional constant. An increase of the velocity by modifying K_p might originate a large overshoot which, in turn, could occasion troubles since Peltier cell may eventually reach temperatures above the upper pain limit (45°C). In this manner, the objective is to attain the same commitment than the case of integrative constant. Figure 3-18 depicts three

Figure 3-18. Three responses with different values of the proportional constant. The graphs show similar behaviours in all cases due to the undue influence of the integrative constant in the response. In this manner, the proportional constant remains in the value given by the Ziegler-Nichols tuning rules (i.e. 16.8)

different responses which do not show marked differences, even though there is a noteworthy swaying in the stationary state when the constant is 14.8, which is flattened when the constant is either 16.8 or 18.8. Therefore, the best option is to select the original constant (i.e. 16.8) to define the definitive PID controller for Peltier cells.

That invariability is probably owing to the value of K_i . The integrative term dramatically increases at the beginning of the procedure due to the high value of K_i and two additional reasons: 1) the significative difference between the steady temperature and the intended set point, and 2) the initial slowness of the Peltier cell. In this manner, the proportional term pushes into the background, although this phenomenon does not affect whatsoever to the performance since the results are adequate and the Peltier cell reaches the target temperatures handily.

Finally, it is necessary to ascertain if a variation of the derivative constant entails changes in the response of Peltier cells. However, there are no significant differences if the constant is slightly varied and K_d remains as the value provided by the tuning rules (see Table 3.2).

Figure 3-19. Five responses with different target temperatures. All responses have similar shapes with rise times around 10 seconds ($\pm 5\%$). The controlled system always reaches the stationary state, even though the plots corresponding to higher temperatures show slight variations around the target temperature.

Despite the variations of all constants, there is no apparent solution to entirely remove the stationary state error during the operation of Peltier cells. All plots show some oscillations around the stationary value (set point) after adjusting the constants empirically, but they are owing to inherent variations to the thermal sensor. Even so, the responses always remain with errors inferior to $\pm 5\%$ regarding the target temperatures, which is fair enough to ensure the proper operation of the thermal system.

The definitive PID controller for the heating case of a Peltier cell has the following values: $K_p = 16.8$, $K_i = 1.9$, and $K_d = 0.6$. Figure 3-19 depicts four responses for different target temperatures. The behaviour is similar in all cases, and rising times ($\pm 5\%$ of the target temperature) are always slightly above 10 seconds.

The procedure to obtain the PID constant for the cooling case is essentially similar. In this case, there is an adjustment of both proportional and integrative constants to accomplish the appropriate cooling of the Peltier cell. As in the heating case, the variation of the derivative constant does not entail significant changes in the response. The definitive constants are $K_p = 13.5$, $K_i = 2.65$, and $K_d = 0.75$. Figure 3-20 depicts four responses with the definitive PID controller, showing the same behaviour with dropping times between 8-10

Figure 3-20. Four responses with different target temperatures. All responses have similar shapes with drop times around 8-10 seconds ($\pm 5\%$). The system always reaches the stationary state with minimal errors, even though there are slight variations over time, but they are no significant whatsoever.

seconds in all cases.

The overall control system of the haptic vest needs to modify the directionality of PID controller during the operation of the whole thermal actuation system, depending on whether the VE sends a signal to render hot or cold temperatures over the user's skin.

3.4 Impact Feedback

An impact stimulus creates a force over the user's skin, but it also stretches and presses the skin. Therefore, these stimuli activate those mechanoreceptors that detect vibrotactile stimuli and alternative mechanisms related to kinaesthetic feedback. As with the thermal stimuli, an impact stimulus may unleash painful sensations and even bruise the stimulated area; thus, it is required stimuli with conservative forces not to harm users.

The impact feedback provides sudden stimuli that can be related to various events stemming from whichever VE. Nevertheless, since the haptic vest gears towards for military

training scenarios, the impact actuation can simulate events such as a virtual gunshot when users confront terrorists wielding firearms.

The impact actuation may be used alongside the vibrotactile or thermal feedback to develop more sophisticated stimuli. Besides than firearms, an assailant might also cause an explosion which, in turn, would generate a blast wave that the vest could render as a combination of vibration in order to simulate the blast wave, a temperature increase to simulate the heat released by the explosion, and an impact to simulate pieces of shrapnel that reach users.

It is hence necessary to select the actuators among the available options besides determining the appropriate method to control the impact feedback together with the rest of vest's systems.

3.4.1 Methods of Actuation

As stated above, the objective of the impact actuator is the creation of moderate forces that can be readily perceived by users in order to identify them as shots or blows of physical objects. There already are some systems to create impact feedback, but mainly based on EMS systems [120], which are not able to simulate a realistic physical blow since the electrical stimulation does not similarly affect the muscles as a physical impact. Moreover, there are mechanical developments gear towards mobile applications for arms or hands [123] but they are not capable of creating strong blows to stimulate the torso (front and back) properly.

There are additional options to create impact feedback, for instance, tactile, pneumatic, or hydraulic systems. On the one hand, the vibrotactile actuation cannot create strong blows, and users could misunderstand the stimuli, confusing them with other virtual events since those actuators can only develop minimally powerful forces. On the other hand, pneumatic or hydraulic systems require a large number of pipes, valves, a compressor, and the end actuator. All those elements would enlarge the weight and the bulkiness, which lead to discarding those systems.

The last option is the usage of commercial actuators that can create impact feedback, adapting them to the vest's necessities, for instance, a linear solenoid. Nevertheless, the available systems are rather bulky, and the developed forces are generally weak, and not enough to simulate an impact. There are similar devices able to develop stronger forces, but its price is considerably larger, and they are unsuitable for the integration into the vest because of the high costs involved.

In the light of the scarcity of research and the inability to applicate the commercial systems in order to generate dependable impact feedback, the more appealing option is the development of a new impact actuator based on a mechanical system, entirely from scratch. Even though there exist mechanical systems, they are not able to develop strong impacts over the areas covered by the haptic vest.

The development of the new impact actuator is stated throughout the following sections, exposing the mechanical design alongside the actuation system and the driver circuit to control the impact stimuli displayed over users.

3.4.2 Design of the Impact Actuator

The mechanical system consists of several movable parts which generate the impact feedback through releasing a preloaded piece in order to contact the user's body. The system generates a blow with an intended force to be handily perceivable by all users.

The main component is a motor which moves the mechanical parts to load a spring that, at a specific point of time, is released, moving the firing pin to generate the impact. Both the motor and the spring must be carefully selected so that the mechanical system reaches the demanded strengths, even though it must avoid overly strong impacts in order not to activate the mechanical nociceptors and generate painful sensations.

Selection of the Spring and the Motor

The critical element of the mechanical system is the spring since it determines the strength of the impact stimuli. Several springs were tested to ascertain if they can generate the enough strength to create an adequate impact. The spring was attached to a piece similar to the firing pin, seeking to have identical conditions than the future impact actuator. The selected torsion spring has a torque given by (3.5), which fulfils the requisites regarding the required motor torque to create appropriate impact stimuli.

$$\tau = k \frac{\theta}{M} \quad (3.5)$$

The other elements of (3.5) are the elastic or torsion constant (k), the deflection angle (θ), and the moment or torque that the motor needs to develop the target force (M).

The main characteristic of the selected component (Model 1217579; Essentra Components, Milton Keynes, UK) is the torsion constant ($k = 5.31 \text{ N/mm}$). Figure 3-21 shows the spring.

The next step is the selection of a motor which can rotate the spring, developing the required strength to create the stimulus. There are two possibilities: stepper and linear motors.

A stepper motor rotates a specific quantity of degrees when the power supply provides an electrical impulse. The motor can rotate a multiple of that value (defined at the datasheet) by controlling the impulses. The primary advantage of these motors is the easiness to handle its operation. The motor can complete a specific rotation, releasing the impact mechanism right on cue to avoid bounces or double impacts. Conversely, the main drawback is related to the necessity of a slightly complex driver circuit based on an H-bridge.

Figure 3-21. The impact actuator contains one torsion spring to load the mechanism and create an impact readily perceivable by users (left image), and a motor that fulfils the requisites regarding the torque to create enough strength for the impact feedback. The linear motor rotates until the spring loads the actuator to generate the stimulus (RS Components, Corby, UK - uk.rs-online.com).

The linear motors operation consists of a continuous rotation during the time that the supply is powering the motor. In this case, the driver circuit is more straightforward since only requires a switch (usually a transistor) to activate the motor (a digital output of the controller). Moreover, it requires a feedback system in order to know whether the actuator is loaded, stopping the motor operation until the VR system sends a signal to trigger an impact stimulus.

Some features of every motor must be analysed to determine if the actuator is appropriate to create the demanded impact:

- The voltage must be lower or equal than 5 V to employ the same power supply as vibrotactile and thermal actuation systems.
- The motor must have a limited size not to increase the weight and the bulkiness of the vest.
- The motor must be capable of developing a torque enough to move the mechanical system and twist the selected spring.
- The electrical current handled by the motors must be small not to increase the temperature of the driver system or engender malfunctions of the vest.

Firstly, it is needed to analyse several motors in order to verify whether they fulfil the requisites regarding voltages and current values. The torque range is variable; thus, three motors are selected in order to carry out a thorough analysis and prove if the available torque is valid for the impact actuator.

The tested motors are two stepper motors manufactured by Nanotec (Nanotec Electronic GmbH & Co. KG, Feldkirchen, Germany) and a linear motor of RS Components (RS

Table 3.3
Features of the linear motor for the impact actuator

Motor	Type	Voltage (V)	Current (A)	Torque (N·cm)	Size (mm)
SP1018M0204-A	Stepper	3.3	0.22	1.6	17.8
SPG1518M0504-50	Stepper	5	0.5	135	20
951D-RS	Linear	5	0.32	3.92	10

Components, Corby, UK). The linear motor and one of the stepper motors have a reduction gear to increase the available torque of the original motor. Their key features are shown in Table 3.3.

The analysis yields that all motors are capable of moving the mechanical system and twisting the selected spring and, therefore, the three motors are valid for the design of the impact actuator. In such a manner, the final decision rests with the size of motors and the intricacy of the driver circuit.

The size of motors is primarily characterised by the diameter, which varies between *10* and *20 mm*. The three motors are valid for a small mechanical design since it only needs minimal adjustments to house and fix the motor appropriately, even though it is always preferred the smallest motor.

The driver circuit does not substantially change according to the kind of motor and, thus, there is no limitation. Thereby, since all the analysed motors are capable of generating the demanded impact, the linear motor (see Figure 3-21) is selected due to the size features shown in Table 3.3. The design of the driver circuit for the selected motor appears in Annex A.

Mechanical Design

The mechanism of operation consists in the rotation of a linear motor that, using a metallic piece, rotates the spring to load the firing pin until a specific position. The system detects the firing pin is in that position and stops the rotation. Where the VR system sends a signal to simulate impact feedback, the linear motor continues its rotation, releasing the firing pin to create the impact stimulus. Unlike a typical gun, the firing pin itself impacts the user and creates the stimulus.

The mechanical design consists of three aluminium and three rigid-plastic (Tough Resin (RS-F2-TOTL-05); Formlabs Inc., Somerville, USA) pieces which guarantee the robustness of the whole system. All pieces (plastic or aluminium) are designed using CATIA (Dassault Systèmes SE, Vélizy-Villacoublay, France), and all plastic pieces are manufactured using the 3D Printer Form 2 (Formlabs). The actuator further contains the motor, the spring, and a switch to stop the operation when the system is ready for creating a stimulus. The entire actuator is shown in Figure 3-22, although their pieces (see Figures 3-23, and 3-24) and the

Figure 3-22. The impact actuator is composed of a mechanical system (the spring and several pieces to create the impact), the linear motor which rotates to load the mechanical system, and a push-button to send a signal to the driver circuit when the actuator is fully loaded and ready to create the impact.

corresponding functionalities are minutely explained next.

The base of the actuator consists of a piece of rigid plastic with two different areas (see Figure 3-23): the area to fix the selected motor, and the area which contains the firing pin, the mechanical transmission system, and a flange to affix the torsion spring. The second area allows the movements demanded to load and release the firing pin. The bottom of the piece has six holes to attach the actuator to the vest using three small coiled wires.

The motor is connected with a metallic cam which transmits the torque from the motor to the firing pin. The cam is made of aluminium in order to prevent wear since it continuously contacts with the firing pin (see Figure 3-24). A metallic piece also avoids breakings because the aluminium is more robust than plastic, and the system develops medium-level strengths during the operation.

The base body of the firing pin is also made of plastic, even though it has an aluminium cover because of the same reasons about wear and endurance (see Figure 3-23). The firing pin has a small aperture with an inner circular protrusion to place the spring, although it also serves to screw the firing pin to the base using a bolt and a nut to accomplish a durable fastening.

The contact between the cam and the firing pin is carried out using an aluminium roller on the opposite end of the firing pin. The cam exerts the torque over the roller to rotate

Figure 3-23. The base (left image) contains a space to place the motor which, in turn, is covered by the cap (right image). That cap also contains a space for placing the button to stop the motor’s operation after the actuator is loaded. The firing pin (central image) is fitted to the base, and it is the piece which creates the impact. All pieces have been designed by using CATIA.

the spring until the firing pin is released and the impact takes place. The roller is affixed to the firing pin using a bolt and a nut anew (see Figure 3-24).

The remaining piece of the actuator serves as a cover for the motor to attach to the actuator securely besides protecting from external influences. That piece of plastic also houses the switch that the cam pressures to communicate to the controller that the actuator is preloaded and ready for creating the next stimuli (see Figure 3-23).

3.5 Overall Control of the Haptic Vest

All actuators previously stated are embedded in the vest aiming to create haptic feedback over users while they visualise a virtual scenario. The VR system generates signals corresponding to virtual events, which sends to the vest so that the driver circuit of each actuator creates the proper feedback according to the received instructions. Therefore, the VR system and the haptic vest must work coordinately to accomplish a synchronised visualisation and perception of virtual events, attempting to increase the system’s realism and the subjective perception of the VE.

The synchronised operation is managed by an overall control system which handles the traffic of information between both systems. The system efficacy lies in accomplishing the

Figure 3-24. The firing pin is moved by the cam (left image), pressing the torsion spring until the actuator is loaded. When the VR system requires an impact, the cam continues its rotation, and the firing pin is released to create the impact stimulus. The roller (right image) is attached to the firing pin and is the contact point between the cam and the firing pin. All pieces have been designed by using CATIA.

communication as swiftly as possible to simultaneously perceive events through both the sense of view and the touch. Thus, the connection between the VR system and the vest gain on importance since it is the key to optimise communication and achieve optimal operation.

There are two alternatives: on the one hand, a wired communication which ensures a swift data transmission; on the other hand, a wireless communication which might be faintly slower despite the vest becomes stand-alone, uniquely needing a short distance between the VR system and the vest during the operation in order to guarantee the communication.

3.5.1 General Driver Circuit

There are two possibilities to control the actuation systems: on the one hand, an Arduino board; on the other hand, a microcontroller whose features provide more versatility to configure and handle the operation of the haptic vest.

Arduino-Based System

The Arduino-Based (AB) haptic vest offers a greater easiness to control and develop haptic stimuli. This system has several limitations related to the storage of information or the number of outputs, which may not be enough to handle high quantities of actuators. However, this version is fundamental for easing the design and the development of the haptic vest.

Most of extant Arduino boards are big-size developments which ease the programming and connectivity with external systems such as actuators or sensors. These boards may have

a considerable number of outputs (up to 11 PWM outputs), that is a foremost requisite to achieve the miniaturisation of the system, and accomplish a handy integration into the haptic vest.

The selected board is the Arduino Lilypad (Arduino, Italy) which is oriented to textile technological developments. It has the customary functionalities of a standard Arduino board regarding power or communication, but it solely has 7 PWM outputs which are not enough to control several vibrotactile, thermal, and impact actuators concurrently. Therefore, the vest would need several identical boards connected between them to allow the simultaneous operation of all actuators settled in the vest.

Although the distribution of actuators over the vest is a matter that is further discussed in future chapters, extant researches already indicate the need of numerous vibration motors to cover the entire vest, seeking to ensure the creation of versatile haptic patterns. In this manner, the final quantity of vibration motors evinces the necessities regarding digital and PWM outputs since thermal and impact actuators have less stringent requirements.

The control of 45 motors requires 7 Arduino Lilypad boards, which would considerably increase the bulkiness and weight of the vest. The usage of the TLC5940 driver (see Annex A) would allow reducing the number of boards since a single board can handle up to 16 motors and, therefore, the vest would only need three boards to manage all vibration motors.

The usage of the TLC5940 driver implies that an Arduino board cannot take on controlling more actuators (only 16 motors). If there are 45 motors, eight Peltier cells, and four impact actuators, two boards would be necessary to handle thermal and impact systems.

A single Arduino board is not enough to handle the entire actuation system of the haptic vest. However, the exact number of boards is defined after the attainment of the experiments about haptic perception in the torso (front and back) (Chapter 4). The communication does not hinge on the final number of boards since the I²C protocol does not limit the number of nodes. In this manner, all the boards are connected using the same bus cable to create a network and to control the actuators of the entire vest simultaneously.

Figure 3-25 shows a whole control system based on Arduino Lilypad boards. All boards are connected between them to allow communication via I²C protocol. In this case, the PCBs to manage the operation of vibrotactile actuators contain the TLC5940 driver to manage 16 motors by PCB.

Microcontroller-Based System

The overall control substantially improves using the Microcontroller-Based (MB) haptic vest. Even though the functionalities might be similar in some cases, the microcontrollers offer some advantages related to electrical parameters, or communication protocols, among others. In this case, the advantages of this particular application are:

Figure 3-25. The system is composed of 7 Arduino Lilypad boards connected between them to conduct the communication via I₂C. Every board connects with a PCB (two on the upper part and two on the lower part of the vest) which control the operation of vibrotactile and thermal actuators. The cables in the bottom of the image power the driver system, which are connected to a wall outlet.

- Improved options to configure the PWM outputs and the processing of haptic patterns. Every register and parameter is modifiable, and controllers have more options to configure several operation modes.
- Large number of outputs: digital, analogic, and PWM.
- Improved processing velocity (i.e. operating frequency). The system responds more swiftly, and it can be adjusted to adapt the velocity to the system requirements.
- Large storing capacity which is useful to keep all the required information to operate the vest in the internal memory of the microcontroller.

The selection of the suitable microcontroller is based on two main objectives: a large number of PWM outputs in order to reduce the number of necessary microcontrollers to handle the operation of all actuation systems; besides a large storage capacity to save all the information required for the vest operation.

The maximum number of PWM outputs is 11 for all available microcontrollers, which implies that every controller can handle the operation of, for instance, ten vibration motors and a Peltier cell. It is thus needed to set up a communication between several controllers to manage a large number of actuators, even though it is feasible the usage of the TLC5940 driver as well. Nevertheless, it is preferable to create a network of several controllers since the communication is rather simple in comparison with the configuration of TLC5940 drivers, and it provides enhanced functionalities regarding storage memory or processing capacity.

Even so, there is another trouble to solve since the communication also reduces the number of available PWM outputs (there are several PWM pins which are needed to configure the communication between controllers). The solution to controlling all the actuators is the division of the vest into several areas and a single driver circuit to manage every specific area. This method reduces the number of actuators to control with the same microcontroller, entailing two benefits: larger miniaturisation of the control system as well as more flexibility to place driver circuits over the vest, reducing the bulkiness and easing the movements when users wear the vest.

The selected device is the PIC18F47J13-I/PT, attending to the demanding requirements about outputs. It is manufactured by Microchip (Microchip Technology Inc., Arizona, USA), and contains 11 PWM output pins. Some of these outputs are demanded to carry out other tasks such as communication or to serve as analogue inputs. Therefore, the best option is the usage of two synchronised microcontrollers to ensure concurrent operation of all subsystems (communications, sensing, etc.) and the associated actuators. All connections between microcontrollers and actuators are printed in PCBs, which further contain the power stages. Both controllers communicate between them via I²C as well.

The microcontrollers need some additional components to handle the entire control system correctly. For instance, the operating voltage range of the selected microcontroller is

comprised between 2.0 and 3.6 V, whereas the driver circuits of the actuators (vibrotactile, thermal, and impact) are powered with 5 V. Hence, the circuit must adapt the power supply to the voltage required by the microcontrollers. The driver uses a linear voltage regulator (LM317T/NOPB; Texas Instruments, Dallas, USA) to transform the supply voltage into 3.3 V. The regulator further needs two additional capacitors ($0.47\ \mu F$ and $33\ \mu F$) to maintain the stability of the system during transients.

The programming of the entire vest requires ample memory storage since the control system deals with plenty of information about actuators or communication, among other systems. The microcontroller has 128 Kbytes to storage programming instructions for the essential operation and the communication of driver systems with the VR system.

However, every pair of microcontrollers handles around 10-15 actuators (the final number is defined afterwards), which entails an outstanding amount of instructions that, in turn, may imply a slowing down of the processing whether the memory is fully used during regular operation. In this manner, some instructions must be stored in an external component: an EEPROM memory of 1024 Kbytes (24AA1025-I/P; Microchip Technology Inc., Arizona, USA), whose chief aim is the storage of the configuration of haptic patterns. The memory is needed since patterns contain a large number of instructions due to the constant changes on the vibration intensity or the temperature throughout the entire sequence.

The microcontrollers require a connection with an external tool (ICD4 In-Circuit Debugger, Microchip) to load the programs developed in the Microchip Integrated Development Environment (IDE) (MPLAB X IDE, Microchip). The driver system includes an RJ12 female connector (MHRJ126P6CR; MH Connectors, Wellingborough, UK), which needs a capacitor ($0.1\ \mu F$) between power and ground to avoid flaws. The driver ultimately contains an additional capacitor (330 nF) and two resistors ($10\ k\Omega$ and $100\ \Omega$) to ensure the correct loading of programs according to the datasheet of the microcontroller.

The same RJ12 connector must serve to program both microcontrollers in order to miniaturise the driver circuit as much as possible. To this end, the circuit includes a sliding actuator (AYZ0202AGRLC; C&K, Waltham, USA) which allows shifting the connection between both microcontrollers.

Finally, a female DC connector (Wurth Elektronik, Waldenburg, Germany) provides the supply voltage of the whole circuit. The system also includes a reset button (EVQQ2F01W; Panasonic Corp, Kadoma, Japan) in order to allow the reboot of the control system in the case of troubles which endanger the operation of the haptic vest.

A large number of components of the driver circuit might be a problem concerning the miniaturisation of the circuit and its placement over the vest since it might hinder the continuous and comfortable usage of the haptic device. All components of the driver circuits are distributed on two different PCBs that are connected one on top of the other through male-female connectors (see Figure 3-26).

Figure 3-26. Two different PCBs compose the driver module. The top PCB contains the MiWi module to communicate with the VR system, a microcontroller, and the driver circuit to control the Peltier cell and the temperature sensor. The bottom PCB contains another microcontroller, the EEPROM memory, and all driver circuits to control the vibration motors. Moreover, that PCB also contains the elements to power the entire module, and an RJ12 connector to program both microcontrollers. Both PCBs are coupled via male-female connectors.

Even though this section stated the components of the driver circuit, the definitive circuit eventually depends on the final number of actuators to cover the entire vest so that users can perceive haptic stimuli over the selected areas of the torso. The exact details are set up after the conclusion of the experiments to ascertain the human perception of the entire torso.

3.5.2 VR System - Vest Communication

The driver circuits of every area do not handle the communication between the vest and the VR system. To that purpose, there are two likely options according to the system is based on Arduino boards or microcontrollers.

In the case of the AB vest, a cable connects the VR system and a PCB of the network controlling the haptic vest. The main advantage of a wired connection is a swifter transmission of data stemming from the virtual scenario since the cables are hardly affected by interferences or signal losses. By contrast, there are drawbacks such as the restraints of movements since the vest and the rest of the hardware are continuously connected to the VR system. Hence, there is more likelihood of breakings or disconnections during prolonged usages of the haptic vest.

Conversely, the MB vest uses a wireless system to carry out the communication. This system consists of two phases: a communication between the VR system and an intermediate

stage, and the communication between that stage and every individual area of the haptic vest.

The VR system mainly consists of a laptop with high-quality technical features and the HMD to visualise the virtual scenario. The laptop must have an integrated Bluetooth system to ease wireless communication with the vest, besides avoiding the necessity of an additional Bluetooth emitter. Figure 3-27 shows the general structure of communication between the VR system and the haptic vest.

The initial idea is to carry out direct communication between the virtual scenario and the vest's areas without an intermediate stage. However, there are two drawbacks:

1. The Bluetooth modules are costly. The usage of a module for every single area of the vest would substantially increase the price.
2. The connection between more than two Bluetooth modules is undoubtedly complex. This drawback is thoroughly explained next.

The second drawback is related to the delivery of information between several modules, and it is the main reason to develop a system with an intermediate stage. If the vest is divided, for instance, into ten different areas, there are ten control subsystems and, in turn, ten Bluetooth modules. When a virtual event occurs, the system sends the information to every subsystem via the Bluetooth connection between the module which origins the signal and one of the ten vest modules. Nevertheless, the information exchange only takes place if both modules are paired. There can only be two paired modules at the same time, and thus if a virtual event affects four different areas, the sending process requires four successive pairings. The procedure becomes very slow, and it is not feasible to properly coordinate haptic feedback and the visualisation of events.

The MiWi wireless protocol does not need continuous pairings, and it can execute concurrent communication. Moreover, the protocol allows the creation of a network with up to 128 nodes (the coordinator and 127 end nodes). Every end-node has a different address which is known by the microcontroller handling the coordinator, so it can simultaneously send the information to all the end nodes. Thereby, this protocol generates a swifter communication between several modules.

Therefore, the intermediate stage serves to receive the information coming from the virtual scenario via Bluetooth (RN41-I/RM, Microchip) and, subsequently, to send that information to the vest via MiWi modules (MRF24J40MA-I/RM, Microchip). The stage is also divided into two PCBs which are one on top of the other employing male-female connectors (see Figure 3-28).

The lower PCB contains the Bluetooth module and a microcontroller to handle the operation of the whole stage. There is an RJ12 connector (to program the microcontroller), a reset button (to restart the operation due to whichever trouble), and a linear regulator

Figure 3-27. The VR system sends signals via Bluetooth communication until a Bluetooth receiver whose control hinges on whether the system uses Arduino or microcontrollers. The AB version has a single receiver, and the master board transmits the signal to the rest of the boards to manage the actuators' operation via I₂C connection. On the other hand, the MB version has a master module which receives signals coming from the VR system and distributes the signal to the modules of the correspondent areas which have to display a haptic pattern via MiWi modules.

Figure 3-28. Two different PCBs compose the external communication module. The top PCB contains the MiWi module to communicate the master with the different areas of the vest. The bottom PCB contains the Bluetooth receiver to get the signals stemming from the virtual scenario. Moreover, this PCB also contains the microcontroller to manage the whole operation, the power connector, and the RJ12 connector. Both PCBs are coupled via male-female connectors.

to convert the 5 V of the power supply into 3.3 V required to power both the Bluetooth module and the microcontroller. All these components have similar functionalities than the PCBs of every area in the vest, attempting to ensure the proper operation anew.

The Bluetooth module does not require any additional component since it already includes some elements for stabilisation and protection. The solely requisite is a space of ground surrounding the module on the top of the PCB to minimise radio interferences.

The upper PCB only contains the MiWi module and a similar space of ground to minimise radio interferences as well. Likewise, the MiWi module also contains the components for stabilisation and protection. Furthermore, the end MiWi module in every PCB of the vest also requires the same space of ground due to reasons alike.

In summary, the VR system sends information via Bluetooth until the intermediate stage. The microcontroller then translates that information into simple signals to ease the data processing in the driver circuits of every vest's area. The same microcontroller concurrently sends the signals via MiWi until the end nodes and, finally, every vest's subsystem handles the received information to display the corresponding haptic stimuli with the adequate actuators. In such a manner, users perceive the appropriate haptic stimulus while they visualise the virtual event.

3.6 Textile Design of the Vest

The primary tasks towards the creation of the haptic vest are the selection of actuators, and the design and the development of actuation and control systems. Nevertheless, the textile design is essential to that users accurately perceive haptic stimuli related to events that they visualise in the virtual scenario. The design must be ergonomic so that the conveyance of information is optimal or, otherwise, the technical design of the vest becomes worthless.

An ergonomic design allows the actuators to remain at fixed positions inside the vest, and permanently in contact with the user's skin. Furthermore, another action to guarantee an optimal design and perception is to fit the actuators in customised frames that, in turn, are sewn over the inner vest arranging an organised structure, which may be further helpful to prevent troubles, such as relative movements or cable breakings.

The frames maintain the distances between actuators regardless of users' movements, but those distances are unknown until conducting the experiments about the perception of the torso. The creation of haptic patterns to simulate virtual events is easier if the distribution is similar in both the AB and the MB vest, guaranteeing the optimal performance of whichever vest in any VE.

3.6.1 Inner Structure of the Vest

Although the distribution of actuators strongly depends on perceptual parameters, some matters can be settled even though the exact distribution is unspecified yet. One of them is the necessity of customised frames to maintain the actuators at fixed positions at every moment during the usage of the vest.

Both vibrotactile and thermal actuators need a frame to ensure the attachment over the inner vest. Thereby, the contact surface between the actuators and the users' skin is maximised, users readily perceive haptic patterns, and they can relate the patterns to the corresponding virtual events.

Conversely, the impact actuator is considerably larger than vibrotactile and thermal actuators, and it is not feasible its integration in the inner vest. Therefore, the impact systems must be externally placed over areas wherein there are no other actuators. To this end, the actuators have three holes to attach them by using thin wires without requiring any additional support.

As stated earlier, the vest is divided into several areas to ease a concurrent and handy control of all systems. It is thus necessary several driver systems whose exact number is determined according to the definitive quantity of actuators after the experiments about perception. Every driver system consists of PCBs that need a frame to maintain attached to the vest, protect the boards (since they are close to the body), and reduce the bulkiness of the haptic vest (the whole system to fix the driver system to the vest is shown in Figure

Figure 3-29. The image shows a Peltier cell and a Pt-100 sensor integrated into the vest. The sensor is in the corner of the Peltier cell in order not to hinder the thermal sensation over the user's skin. The structure is composed of several pieces to support the Peltier cell, the Pt-100 sensor, and the heat sink. Moreover, the frame also serves to hold the driver module of each area of the vest.

3-29, whereas the separate pieces are shown in Figures 3-30, and 3-31).

Notwithstanding, the frames are not directly attached to the fabric of the vest because there is an inner modular structure shaped like a triangular mesh. Every node of the mesh has a piece with space to place a vibration motor. In this manner, vibrotactile actuators are uniformly distributed all over the vest at each node. The psychophysical experiments in Chapter 4 determine the dimensions of the mesh in order to place the actuators at distances according to the vibrotactile spatial acuity over the entire torso.

The connections between nodes are hollow rectangular pieces oriented to contain the wiring of the entire actuation system, protecting the cables from outer influences, preventing breakings or disconnections. Both PCB and Peltier-cells frames are designed for its placement in the vertex of a triangle.

As stated above, the final dimensions of the mesh depend on the final number of vibrotactile actuators. Figure 3-32 shows the definitive triangular mesh, but it does not report the dimensions waiting for results of psychophysical experiments. Every piece consists of a node and several arms. There are two holes at the end of each arm to sew adjoining pieces and create the hexagons. Those holes are also used to sew the pieces in the fabric.

The pieces of the mesh are manufactured using the 3D printer stated above. In this case, the material is a flexible resin (RS-F2-FLGR-02, Formlabs Inc.) so that, once the pieces are affixed to the vest, the structure does not restrict users' movements while they wear the

Figure 3-30. This piece (designed by using CATIA) contains all the pieces to hold the Peltier cell, the Pt-100 sensor, and the heat sink. It is placed in the inner vest, and the four legs serve to attach the piece with the rest of the mesh. The piece also holds the external frame wherein the PCBs of the driver module are attached.

Figure 3-31. The left piece serves to support the Peltier cell and the heat sink; the central piece serves to support the PCB of each area using screws and nuts; the right piece is placed on the top side of the Peltier cell to support the Pt-100 and ensure a permanent contact with the same side of the Peltier cell contacting with the user's skin. All pieces have been designed by using CATIA.

Figure 3-32. The triangular mesh contains a motor in each node and allows the routing of cables in the hollows of the legs. The mesh is attached to the vest through the piece which serves as a support for the thermal actuation system and the external driver module of each area (see Figure 3-30).

Figure 3-33. Each node contains a frame for placing the vibration motor. Likewise, the node has space to securely fit the motor in order to prevent relative movements of motors in the haptic vest.

haptic vest. Otherwise, the usage of more rigid materials in addition to a large number of vibrotactile actuators could generate discomfort or movement problems during the usage.

The necessity of a customised frame for vibration motors lies in the results of the characterisation of vibrotactile actuators since they lose part of their capabilities if they are sewn over the fabric directly (see Section 3.2.4). In that case, the motors cannot reach high frequencies, and the available haptic patterns are acutely limited. Contrarily, the reduction of intensity is more moderate with the motor-frame configuration (see Figure 3-9), and it is hence possible to leverage the full capabilities of the motors.

All frames are manufactured using the rigid resin to ease the placement in the nodes and ensure reliable fastening of the motor and the frame. They have to contain two holes to conduct the cable routing and serve as a protection for breakings. Thereby, the motors remain fixed at the nodes of the structure, remaining their features unaffected during the vest's operation. Figure 3-33 shows a frame with the motor placed at a node of the triangular structure.

The Peltier cell and the heat sink constitute the thermal actuation system. Both components must be affixed to the haptic vest using a frame to ensure the permanent contact between the Peltier cell and the users' skin (see Figure 3-29). The sensor of the PID controller must also make enduring contact with the side of the cell contacting the skin, aiming to measure the temperature rendered over users continuously. It is hence demanded an additional frame to keep the sensor attached to the cell, avoiding contacts with the skin not to bias the measure of the actual temperature in the cell.

This frame must also include an area to attach the PCBs of each driver system, seeking to enhance the compaction of all vest's systems as well as its robustness. To this end, the PCB design has a square hole sized as the thermal system to place all components together and ease the heat dissipation. The Thermal-PCB frame is mounted in the inner vest; thus, it is needed a square hole on the fabric to mount all elements. The Peltier cell remains over

the inner area, whereas the PCBs and the heat sink remains in the outer side of the frame. The objective is that the heat sink is capable of dissipating the residual heat to the ambient.

Although the frame is the same for both systems, it is composed of several pieces to achieve the best fastening of all components. The PCB piece has a square hole also sized as the thermal system wherein two additional pieces are attached to secure thermal components. The piece has four holes to screw the PCB, even though the bolts and nuts must be made of non-conductive material to avoid electrical failures when fastening components contacts with a PCB trace.

The PCB frame also serves to anchor the Peltier cell. The square hole contains two flanges to fit the cell between them. The PCB-Peltier frame is manufactured with the flexible resin since it has large dimensions and could hinder some users' movements during the common usage.

Once the Peltier cell is fixed to the frame, an additional piece is fitted between the cell and the flexible frame to place the heat sink. That frame must be made of rigid resin, which facilitates a proper joint between both components. Additionally, the junction between the cell and the heat sink carries thermal paste which also serves as a sort of glue between both elements.

Lastly, the sensor frame is also rigid and, once again, it is fitted between the PCB-Peltier cell pliant frame and the Peltier cell itself. This frame is placed on a corner of the cell side which is contacting with users' skin in order to take up the minimum space, which prevents from defective temperature transmissions (see Figure A-5). It further contains two small holes to wire the terminals of the sensor.

The entire frame is composed of several pieces, but the only component attached to the triangular inner mesh is the PCB-Peltier support. That frame includes four arms whose ends coincide with the joint of the pieces of the inner mesh. They also have two holes to attach the frame both to the inner mesh and the neoprene through strong seams.

The joint design of the frame aims to save space and material, including the driver circuits and the thermal actuation system in predefined locations of the vest. Even so, those frames may be placed over any area, providing that future versions of the haptic vest require more quantity of actuators.

All described frames are distributed over the vest according to the parameters of thermal and vibrotactile perception. In no case, the structure is placed at the laterals or shoulders of the vest. An actuation system over a lateral would demand a PCB system which would hinder the user's movements, and it would add risks for the structural integrity of the vest due to the movements of arms around those areas.

3.6.2 Textile Design

There are two essential factors to consider about the textile design and ergonomics: the fabric and the fitting of the vest to users' body. The objective is to select a fabric which allows an easy adaptation to any sort of body besides an ergonomic textile design which allows the actuators to be in permanent contact with the body, aiming users perceive all haptic stimuli rightly.

The selected fabric is neoprene due to its pliancy, adjustability, and low cost. Thereby, the vests are adjustable to several body sizes, guaranteeing the best wearability and the perception of all haptic patterns. In such a manner, there are two vests (S and L sizes), but they contain some apertures on the laterals and the shoulders so as to readily adjust the vest to the rest of standard sizes (i.e. M and XL). The apertures allow an ample adaptation range by utilising Velcro strips.

The different sizes might entail changes in the number of actuators required to cover the entire torso. Even so, the objective is to maintain constant the number of vibrotactile, thermal, and impact actuators regardless of the vest's size. Therefore, the large vests contain small empty areas, which are not detrimental for perceiving haptic stimuli.

Both laterals and shoulders are not recommended areas to distribute the actuators since they contain fasteners to adjust the vest; they are further uneven and osseous areas which might hamper the perception of haptic stimuli. In conclusion, the actuators are placed exclusively over the front torso (the chest and the abdomen) as well as the back (the dorsal and lumbar areas), avoiding insensitive or uneven areas which could induce discomfort or misperception of haptic stimuli.

Chapter 4

Characterisation of the Haptic Perception over the Torso

A haptic vest aims to accomplish users perceive the same stimuli than the avatar that they control in a virtual scenario. Those stimuli are simulated through haptic patterns that may be composed of several kinds of feedback (in the case of this haptic vest, the stimuli are developed using vibrotactile, thermal, or impact feedback; or even a combination of several types). For instance, a vibrotactile pattern might be a sequence of several vibrations at different intensities in order to indicate that a virtual character is touching the back of the controlled avatar. Similarly, a thermal pattern might simulate a change of body temperature when the avatar is in an outdoor scenario. Moreover, a combined stimulus might simulate an explosion composed of the vibration of a blast wave, a heat increase, and several impacts due to small pieces of shrapnel.

The development of patterns is based on modifying the operating parameters of an actuator during a particular time to generate a specific stimulus. If these patterns simulate the touch events realistically, they might serve to enhance the sense of presence in the VE. The study of the relationship between feedback (vibrotactile, thermal, and impact) and human perception affords to optimise the creation of patterns, attempting to accomplish dependable stimuli that users can readily relate to whichever virtual event.

Forasmuch as the haptic technology has markedly evolved during last years, there are plenty researches about perception's parameters at different areas of the body, even though studies primarily focus on hands or arms [20] [22]. Conversely, researches about the perception of the torso (front and back) are scarce and, hence, some experiments are necessary to determine the parameters of haptic perception over those areas.

The first datum to ascertain is the spatial acuity of vibrotactile and thermal feedback. This parameter sets up the required distance between two simultaneous stimuli to discriminate them as two isolated stimuli, which may be helpful in order to determine the distribu-

tion of actuators over the analysed areas. Defective distributions of vibrotactile and thermal feedback may lead to the overlapping of patterns, or the generation of unwanted phenomena such as spatial summation, unleashing the misperception of haptic stimuli. Contrarily, the impact spatial acuity is not required since actuators are large, and the vest can only contain a small amount and, thus, there is no likelihood of overlapping simultaneous impact stimuli.

The next step is to ascertain parameters to properly configure haptic patterns in order to simulate specific events or sensations. It is then essential to know the limits of perception, which is chiefly related to the frequencies detectable through mechanoreceptors, or the temperatures detectable through thermoreceptors (i.e. the absolute thresholds). Furthermore, determining the minimum difference between two consecutive stimuli to distinguish them as two distinct stimuli eases the creation of haptic patterns (i.e. the differential thresholds).

Regarding thermal feedback, the activation thresholds of thermal nociceptors (receptors which unleash pain sensations) delimit perception through the skin. Although there are slight dissimilarities between studies, a general approach indicates that nociceptors activate at $15^{\circ}C$ for cold stimuli, and $45^{\circ}C$ for warm stimulus. Thereby, it is not necessary to examine these parameters since Peltier cells are capable of generating these temperatures without excessive power consumptions.

However, vibrotactile feedback is undoubtedly more complicated. The range of detectable vibrations in the torso (front and back) is not clear at all nowadays, even though it is primarily related to the range delimited by mechanoreceptors such as Pacinian or Meissner corpuscles ($40 - 500\text{ Hz}$, roughly) [15]. As the selected motors can generate vibrations at intensities between 50 and 300 Hz , the maximum vibration is always perceived. In contrast, the minimum detectable vibration (the low absolute threshold) reveals whether motors render stimuli that users cannot perceive, avoiding the usage of those vibrations for creating vibrotactile patterns.

There is barely any research about vibrotactile differential thresholds, and their values must be determined through new experiments. However, the thermal differential thresholds have been already profusely researched, and values to create thermal patterns can be taken from previous studies [29] [49]. Those thresholds hinge on the velocity at which the temperature changes:

- If the temperature changes rapidly (i.e. several degrees per second), the thresholds are around $0.1-0.5^{\circ}C/s$.
- If the temperature changes more slowly (i.e. several degrees per minute), the thresholds are around $2-3^{\circ}C$.

In this case, the vest always renders thermal patterns to indicate fast temperature changes ($1-2^{\circ}C/s$) and, therefore, users can detect those variations easily [29].

Lastly, the impact feedback neither requires a detailed analysis of the perception thresholds to accomplish a proper operation. On the one hand, the impact strength is always similar to create a recognisable impact by all users; thus, the determination of differential thresholds would be pointless for this application. On the other hand, the study about impact absolute thresholds is not necessary since the strength of impacts always remains constant. The best option is to determine impacts with continual strength not to create discomfort and not activate the mechanical nociceptors in no case; otherwise, the stimulus might cause damages to the top layers of the skin.

All psychophysical parameters allow the creation of haptic patterns that convey the intended information appropriately, and users can recognise the patterns as specific virtual events stemming from the VE.

The following sections expose several experiments to determine the perception of vibrotactile and thermal stimuli over the torso in order to accomplish a dependable creation of patterns to be ultimately rendered using the haptic vest. The two experiments about vibrotactile thresholds take the vibration frequency as a reference, although values can be expressed in terms of amplitude (g) (see equation 3.3) or intensity (Hz – g) (see equation 3.4). The intensity is only used to express definitive results of psychophysical parameters, such as vibrotactile absolute thresholds or particular cases of differential thresholds.

4.1 Vibrotactile Spatial Acuity

The experiments about vibrotactile perception are fundamental in order to develop haptic devices which dependably stimulate users while visualising a virtual scenario. As stated above, there are three essential psychophysical parameters to characterise human vibrotactile feedback: the spatial acuity, the absolute thresholds, and the differential thresholds.

The spatial acuity is the minimum distance to perceive two different vibrations as isolated stimuli. The values serve to figure out the best distribution of actuators over the vest in order to create dependable vibrotactile patterns.

According to the results of the experiment, there are two possibilities to distribute the actuators hinging on the initial requisites of vibrotactile stimulation rendered by the vest:

1. Distribution of vibrotactile actuators at higher distances than the spatial acuity values. Users would be able to identify two adjacent motors vibrating simultaneously. Even so, there would be other phenomena (e.g. the spatial summation) to consider for adjusting the distribution accurately and enhancing the design of haptic vibrotactile patterns.
2. Distribution of vibrotactile actuators at lower distances than the spatial acuity values. Users would not be able to detect two adjacent motors vibrating simultaneously. In

such a manner, the creation of haptic patterns become more laboured, even though this configuration allows displaying generalised vibrations that may be helpful on certain occasions.

Therefore, the final distribution depends on the results of the experiments, the requisites for creating haptic patterns, the available space over the vest, and the capability of the overall driver system to manage a precise number of actuators.

The ultimate decision about the distribution also determines the final dimensions of the triangular mesh described in Chapter 3, Subsection 3.6.1. The length of a side is equal to the distance between two adjacent vibration motors, and that value depends on the spatial acuity values. Even so, the first step to integrate the vest into a VR system is the validation of the design. If spatial acuity values are not adequate so that users perceive vibrotactile patterns accurately, the definitive triangular mesh must be adjusted conveniently to ensure optimal operation of the haptic vest.

Although there are several prior studies about spatial acuity, they chiefly focused on other areas more commonly used such as the hands or arms [43] [44]. Those areas are the primary manner to interact with the surrounding environment through the sense of touch since the active touch (the user triggers a contact) is manageable more readily. Conversely, stimuli over the torso are customarily passive, and the creation of haptic patterns becomes more involved, which results in the scarcity of studies about spatial acuity over those areas.

Comparison between Motors

This experiment also serves to establish a comparison between two different vibration motors in order to ascertain whether there are dissimilarities on the spatial acuity depending on the particular features of actuators (e.g. the vibration frequency, the amplitude or the dimensions of motors). In this manner, the results reveal whether a change of vibration motor implies a mandatory modification in the distribution of actuators over the vest.

The first actuator is the vibration motor stated in Chapter 3, Section 3.2.2 and the second one is the model 308-102 (Precision Microdrives Ltd.), which is an ERM motor as well (see Figure 4-1).

The '308-102' motor can operate at higher voltages and currents and, therefore, it can vibrate at higher intensities. The relationship between voltage, frequency, and amplitude is also linear according to the operating curves of the datasheet (see Figure 4-2). Results of spatial acuity are given in terms of distance, so it is not required a complete characterisation since values remain constant and maximum in the course of the experiment.

Another differential aspect is that the second motor is not encapsulated. Hence, to carry out the experiments, the motors are housed in customised encapsulations manufactured with a 3D printer that allows the rotation of the offset mass without blockages when the actuator

Figure 4-1. '308-102' motor (left image) used in the spatial acuity experiment so as to compare the results between two different motors (Precision Microdrives Ltd., London, England - www.precisionmicrodrives.com). As the motor is not encapsulated, it needs an additional frame to allow the proper operation of the motor, which is manufactured with a 3D printer (center and right images).

Figure 4-2. Performance curves of the '308-102' motor, relating the vibration amplitude (g), the vibration frequency (Hz), the current (mA), and acceleration efficiency (g/W), to the voltage (V) of the motor (Precision Microdrives Ltd., London, England).

Figure 4-3. The upper vest is divided into seven areas to determine the vibrotactile spatial acuity, whereas the lower vest is divided into three areas to determine the thermal spatial acuity.

is close to the body (see Figure 4-1).

The last difference is the size since the second motor measures 20 mm (as the selected motor for the vest), but a diameter of 7 mm (2 mm larger than motors for the vest). However, the encapsulation enlarges the size and the final dimensions are a length of 22 mm and a diameter of 10 mm .

Materials

The experiment is solely carried out over the upper areas of the torso (front and back), even though the vest utterly covers the entire torso. This selection of areas hinges on the initial design of the vest, in which the vibrotactile feedback was only located in upper areas of the vest, whereas the thermal actuation was located in lower areas exclusively.

Both zones (upper torso and upper back) are subdivided into seven different areas (the shoulders; the right and the left torso; and the right, the central and the left back). The central area of the torso is fundamentally osseous, and the vest has a fastener to achieve tight fitting to the body; hence, the placement of actuators over that area was pointless because there would be hurdles to accomplish proper perception of vibrotactile stimuli. Figure 4-3 depicts the definitive subdivision of areas.

In this experiment, the vest is the same for all participants since it can be readily adjusted

using Velcro strips sewed in the laterals of the vest. Furthermore, participants could fasten the vest using a zip to adjust as much as possible to its body. In such a manner, the motors remained in permanent contact with the user's skin to accomplish the best transmission of stimuli.

Vibration motors are placed over a cloth with the approximate size of the delimited areas. The fastening of motors in the cloth must keep unchanging the functional features obtained from the characterisation in Chapter 3, Subsection 3.2.4. To this end, the material of the cloth is polyester, and the motors are affixed using elastic strips. Notwithstanding, the conditions were verified before beginning each experiment to avert variations which would debase the results. The cloth also has two Velcro strips to attach it at fixed positions in the vest for all users. In this manner, motors always render stimuli over the same area regardless of who is wearing the vest.

The last step is to set up the distribution of motors over the cloth, which depends on the motor's size since they are dissimilar. As the cloths have to keep the same dimensions to attach it over the same areas, the cloth with the '304-116' model contains ten motors with a separation of *10 mm* from each other to avoid contacts; on the other hand, the cloth with the '308-102' model contains six motors with a separation of *20 mm* from each other. Keeping those distances is vital to ensure that spatial acuity values provide reliable information about the perception over the entire torso.

Experimental System

The experimental system consists of a controller to handle the operation of the motors (Arduino UNO) which is managed using the Arduino IDE (Integrated Development Environment). The whole system (controller and motors) is managed by a Dell Precision 490 Dual-Core Intel Xeon EM64t (using graphics card nVIDIA®Quadro®FX 4500, 512 MB) running MATLAB to record participants' responses.

Participants

Participants were 24 volunteers: 15 males and 9 females ranging from 22 to 35 years old (mean $\pm$ Standard Deviation (SD), 25.79 ± 2.99 years). All participants were unaware of the purpose of the study. 20 participants were students at Universidad Politécnica de Madrid, whereas 4 participants were external from the institution.

The participants must be older than 18 years and younger than 40 years since age is a leading factor in haptic perception [238] [239] [240]. One of them indicated a neuropathology that could affect the right side sensitivity, and their results over the right areas were discarded. All participants provided informed written consent after the explanation of the whole procedure. Figure 4-4 shows the vest during a phase of the experiment.

Figure 4-4. The cloth with the motors is placed at every area in 4-3 to determine the spatial acuity for all participants.

The Ethics Committee of Universidad Politécnica de Madrid approved the experimental procedures. The study complied with the Code of Ethics of the World Medical Association (Declaration of Helsinki).

Experimental Procedure

The experiment consists of two phases to ascertain the spatial acuity values with both motors. Each phase affords to determine the results with a vibration motor but always following the same procedure.

The ten motors of the '304-116' model keep distances of *10 mm* from each other (see Figure 4-5); thus, the obtained results can only be multiples of 10. Therefore, there are nine possible values since the maximum distance is *90 mm* (the distance between the first and the last motor), whereas the minimum distance is *10 mm* (the distance between two contiguous motors). Although results are discrete, they are powerful to approximate the spatial acuity value for the analysed areas, as well as accomplishing an appropriate distribution of motors over the vest.

The orientation of motors is always vertical (see Figure 4-5). Results provide the diameter of the vibratory receptor field over different areas of the torso. Therefore, the motors' placement is irrelevant since the spatial origin of vibration is the same independently on motors' orientation is vertical, horizontal or diagonal.

Nevertheless, '308-102' motors generate slightly different results. The distances between motors are *20 mm* (see Figure 4-5); thus, the results are obtained as multiples of 20. Hence,

Figure 4-5. The left image shows the ten '304-116' motors in the cloth fastened with elastic tapes to avoid relative movements throughout the experiment. The right image shows the six '308-102' motors fastened with the same method to avoid likely displacements.

results are even less accurate, but they serve to establish a comparison with the results of the other motor. In such a manner, it is possible to elucidate whether there are differences between motors with different features (both dimensional and operating).

In the first phase ('304-116' motor), the cloth is placed at the seven areas wherein the vest has been divided previously in order to settle the spatial acuity value for every single area. However, the second phase of the experiment ('308-102' motor) only tests four areas of the torso (right/left front, and right/left back), seeking to determine some comparison values.

The sequence consists of 18 stimuli of two motors vibrating simultaneously during the first phase (i.e. the first motor). The sequence ensures the presentation of two vibrations at all possible distances (two at 10 mm , two at 20 mm , and so forth). The motors that vibrate at every distance are random except for the longest distance (90 mm) since only the first, and the last motor maintains that clearance. Furthermore, the sequence of presentation of distances is randomised to avoid biases.

Each pair of stimuli lasts one second. The temporal gap of 5 seconds gives enough time to participants for responding if they have felt a single vibration or two simultaneous vibrations. Participants press 1 or 2 on a numeric keyboard depending on the perceived stimulus.

The unique difference between the sequence of the first and the second motor is the total number of vibrations. The second phase consists of ten vibrations to render two stimuli at every distance, given that there are solely six motors.

All vibrations during both phases are at the maximum intensity reachable by the correspondent motor. The controller uses PWM to maintain permanent intensity during the whole experiment. In this manner, the '304-116' motors always vibrate at 320 Hz , whereas

the '308-102' motors always vibrate at *360 Hz*.

Each participant repeats the procedure 11 times to get the spatial acuity value for each area and motor (7 areas with '304-116' motor and four areas with '308-102' motor). The completion of the experiment (the seven areas of the first motor and the four areas of the second motor) generally lasts an hour. There is a temporal gap (3 minutes) between areas to reduce the fatigue and to encourage concentration throughout the experiment. Figure 4-6 shows a schematic of the whole procedure to ascertain the vibrotactile spatial acuity.

The testing order of areas during both phases is random as well. The experimental system generated a random order before beginning the experiment. In this manner, after finishing an area, the researcher placed the cloth over the next area of the vest, participants wore the vest, and the sequence started so that they responded to determine the spatial acuity in that area.

Before beginning the first phase, participants are instructed with some preliminary vibrations so that they become accustomed to the stimuli during the rest of the experiment. Those vibrations allow users to perceive all stimuli rightly during both phases, avoiding jeopardised responses owing to lacks of perception.

Lastly, participants hear an intense white noise during the experiment in order to mask the sound of motors so that the responses are based only on the perceived vibration. The noise starts some milliseconds after starting each vibration and stops when vibrations finalise to indicate that participants have to respond using the keyboard. The volume is adjusted to avoid discomfort in users, providing that the sound of vibrations remains masked.

Statistical Analysis

The experiment affords to acquire the spatial acuity values with two experimental conditions besides comparing the results to ascertain likely differences between areas or motors. The statistical analyses are always non-parametric tests since discrete values cannot follow a normal distribution. The selection of the test hinges on the number of possible values (dichotomous or non-dichotomous variables) and the relation between those variables. There are three possible comparisons:

1. Comparison between the first and the second motor as a function of the analysed areas. The objective is to ascertain if the usage of different motors entails a change on the spatial acuity values. The analysis is performed using a Wilcoxon signed-rank test for two related samples since the same participants perform both phases.
2. Comparison between all analysed areas with each motor. The objective is to ascertain if the spatial acuity changes depending on the area of the torso (front or back), aiming to distribute the actuators evenly in the entire torso. The analysis is performed using a Kruskal-Wallis test by ranks to compare seven (first motor) or four areas (second

Figure 4-6. The scheme shows the sequence of events to complete by the experimenter and the participant to finish the whole vibrotactile spatial acuity experiment. The whole experiment lasts around one hour.

Figure 4-7. Values of vibrotactile spatial acuity for the seven analysed areas. Each marker represents the median of all subjects in each area, and the error bars correspond to the IQR. The dashed line is the median of all spatial acuity values (50 mm), and the solid lines represents the IQR of the general results $[37.5\text{ }57.5]\text{ mm}$.

motor). If some of these tests generate significant results, it would be required to carry out a Wilcoxon post-hoc test to determine differences between specific areas accurately.

3. Comparison to find out likely differences between male and female participants, both with the first and the second motor. The analysis is performed using a Mann-Whitney U test for non-related samples.

Furthermore, since values are discrete, the mean of results is not the best manner to measure the central tendency of every group of samples. A better option is to use the median to measure the central tendency, besides the Interquartile Range (IQR) to measure the statistical dispersion of results.

Results

The experiment yields a single value of spatial acuity for every analysed area. Figures 4-7 and 4-8 shows the median as a function of each area for both motors. In both cases, the results fluctuate between 40 and 60 mm depending on the area. The dashed line denotes the median of all values, whereas both solid lines denote the upper and lower limits of the IQR for every motor.

The Wilcoxon test serves to compare the values obtained with both motors for every analysed area (see Table 4.1), but results do not show significant differences in no case (all p-values are higher than 0.05). Therefore, the distance to discriminate two simultaneous stimuli are roughly equal independently on the selected motor.

Figure 4-8. Values of vibrotactile spatial acuity for the four analysed areas. Each marker represents the median of all subjects in each area, and the error bars corresponds to the IQR. The dashed line is the median of all spatial acuity values (60 mm), and the solid lines represents the IQR of the results $[40\ 60]\text{ mm}$.

Table 4.1
Statistical results of the comparison between the '304-116' and the '308-112' motor in the vibrotactile spatial acuity experiment

Area	Statistic (F)	p-value
Upper Right Front	51	0.391
Upper Right Back	51	0.079
Upper Left Front	82.5	0.913
Upper Left Back	66.5	0.732

On the other hand, the Kruskal-Wallis test does not show significant differences between all analysed areas, neither with the first nor the second motor. In the first motor ('304-116'), the statistic (F) is 3.556 , and the p -value is 0.737 ; whereas in the second case, the statistic (F) is 3.739 , and the p -value is 0.291 . Hence, the post-hoc test is not necessary since there are no differences between areas.

There is a significant difference in the comparison between male and female participants, according to the Mann-Whitney test. The significant result corresponds to the experiments with the second motor (see Table 4.3). Contrarily, the results of the first phase (i.e. using the motor '304-116') do not show significant differences (see Table 4.2). Therefore, that result is an isolated case which does not affect the development of the vest whatsoever.

Table 4.2
Results of the Mann-Whitney test for comparing vibrotactile spatial acuity
values of males and females for the '304-116' motor

Area	Statistic (F)	p-value
Upper Right Front	62.5	0.539
Right Shoulder	87	0.053
Upper Right Back	77	0.064
Central Back	51.5	0.636
Upper Left Front	82	0.111
Left Shoulder	42.5	0.280
Upper Left Back	63.5	0.401

Table 4.3
Results of the Mann-Whitney test for comparing vibrotactile spatial acuity
values of males and females for the '308-112' motor

Area	Statistic (F)	p-value
Upper Right Front	51	0.016
Upper Right Back	51	0.278
Upper Left Front	82.5	0.346
Upper Left Back	66.5	0.269

Discussion

The results of analysed areas are within a range comprised between *40* and *60 mm*, but the statistical analyses do not show any significant difference among all areas, probably due to the high values of IQR in Figures 4-7 and 4-8. Hence, a single value is the reference to conduct the distribution of vibrotactile actuators over all areas of the upper vest.

Nevertheless, it is engaging to compare results of both phases, although the resolution is lower (values are given in multiples of 20 for the second motor) due to the larger dimensions of motors. Values are somewhat alike, and the median of all areas are within the same range anew (*40-60 mm*). Moreover, the statistical analysis does not show significant differences, proving the similarity of values in all tested areas.

The most appropriate distance to place the actuators must be a conservative value to ensure a distribution that considers the spatial acuity values of all areas. Selecting the higher result (i.e. *60 mm*), users can readily distinguish all stimuli of a haptic pattern over whichever area of the torso.

There are previous studies about the spatial acuity on the torso, but results are not consistent between them. First researches yield quite high values (among *1* and *3 cm*) with similar conditions to this experiment [25]. However, recent researches yield values akin to the ones obtained in this experiment (the results vary among *30* and *51 mm* depending on

several experimental conditions) [23] [48].

Notwithstanding, there are two issues which make initially inviable to apply prior results in the design of this haptic vest: the studies use different kinds of motors, and materials wherein motors are attached are entirely different [27]. Even so, results are somewhat similar in some cases, implying that the spatial acuity over the torso does not overly vary according to those aspects. Thus, these values or those of previous researches can be employed as references to design and develop vibrotactile devices, even though it is advisable a preliminary test for guaranteeing that those values maintain with the actuators of the new design.

The comparison between the results of both motors (Wilcoxon signed-rank test) neither yields significant differences, endorsing the previous similarity. Although the second motor is larger and vibrates at higher intensities, it does not induce a lowering of spatial acuity values, entailing that those higher frequencies do not imply a broader spreading of vibrations [33]. Nevertheless, there are researches which show significant differences when motors are substantially dissimilar (concerning their size or functional features) [27]. In this manner, the results are only generalisable providing that the features of actuators are somewhat alike; otherwise, it would be necessary to conduct the experiment anew to attain the values to distribute vibrotactile actuators.

The spatial acuity values provide information about the receptor field of vibrotactile stimuli, which does not differ depending on the orientation of actuators. Vibration motors are always vertically orientated during the experiment, but results would maintain similar if motors would have a diagonal or horizontal orientation.

Both motors vibrate at its maximum intensity and, hence, the receptor field is also maximal. Repeating the experiment by employing lower intensities would result in smaller receptor fields and lower values of spatial acuity. Thereby, using the highest value ensures that users can always discern two adjacent stimuli regardless of the vibratory intensity.

There is an additional aspect to consider: the difference between the maximum intensity of the first and the second motor is around 50 Hz . That value may be the key to understand why the spatial acuity does not vary with different motors, although the verification of this assumption appears in Section 4.5.1 because it is related to values of differential thresholds.

The last statistical analysis seeks to determine likely differences between men and women regarding vibrotactile spatial acuity. There is a unique difference correspondent to values in the Upper Right Front (URF) for the second motor. That difference does not agree with the results of the first motor. The result could indicate absences of concentration or fatigue during the experiments or a defective vest's fitting, but it could probably vanish by enlarging the number of samples. Thereby, there is no enough evidence to categorically assert that there are differences in perception depending on the gender of users.

Hence, the value is discarded to carry out the distribution of vibrotactile actuators since it seems an isolated case with those alternative motors. Even though, that difference could

be meaningful in case of new significant results in subsequent psychophysical experiments.

The material of the vest is a fundamental factor to consider during the experiment and the ordinary operation of the haptic vest. The initial characterisation of vibration motors (see Chapter 3, Subsection 3.2.4) affords to know the features of stimuli rendered by actuators, but it is not a standard procedure in prior researches [23] [48]. Nevertheless, the procedure is undoubtedly useful since other materials affect vibratory responses in unforeseen manners and, therefore, the motors would require repeating the characterisation and the experiments to attain the results correctly.

The initial objective was to determine the spatial acuity using simultaneous stimuli, but offset times could appear during ordinary operations of the vest, which might remarkably affect values of spatial acuity, and the subsequent perception of haptic patterns [48]. Values under those conditions usually yield lower results (the distances decreases) regarding values with null offset times. Thereby, it is more sensible to take the worst case (null offset times) as a reference to distribute vibrotactile actuators, ensuring the perception of all stimuli regardless of offset times during the patterns.

4.2 Thermal Spatial Acuity

Thermal stimuli can generate painful or uneasy stimuli over users due to extreme temperatures, either hot or cold. There are plenty of studies about thermal perception to avoid those situations, seeking to ascertain the critical parameters to create adequate thermal feedback with haptic devices, as well as maintaining users safe during the operation of those devices.

The first matter to consider is the thermal spatial acuity since the distribution of actuators over the vest is indispensable to create reliable thermal patterns. Results afford to set the minimum distance required between two adjacent actuators so that users perceive two simultaneous thermal stimuli instead of a general stimulus.

In such a manner, an adequate distribution lead to the system can develop thermal haptic patterns that users may perceive and relate to virtual events stemming from the virtual scenario.

There are two options to distribute those actuators, depending on the results:

- Placing thermal actuators at larger distances than the spatial acuity value, users can discriminate between two concurrent stimuli.
- Placing thermal actuators at lower distances than the spatial acuity value, two adjacent actuators can generate a generalised thermal stimulus over users if they operate simultaneously.

In this case, although the thermal acuity is an essential parameter to distribute the actuators in the haptic vest, the perception is also subject to other phenomena such as the

spatial summation. That phenomenon is complex to understand and handle due to their unforeseen consequences [17] [40], and it can complicate the perception of thermal stimuli. For instance, two thermal actuators simultaneously heating might originate generalised hot sensations in those areas, but they also could spread sensations to areas not stimulated at that precise instant.

This experiment was conducted in parallel alongside the vibrotactile spatial acuity experiment. Hence, the analysed areas are in concert with the initial idea to distribute actuators over the vest: vibrotactile feedback over the upper torso and thermal feedback over the lower torso (front and back).

Thereby, the experiments are carried out solely over lower areas covered by the haptic vest, which has been divided into the Right Abdomen (RA), the Left Abdomen (LA), and the Lower Back (LB) (see Figure 4-3). Despite that, if results are similar between areas, the values are generalisable, assuming that the distribution of thermal actuators may be equal for the rest of areas in the torso (front and back).

The division of the lower torso on three areas could seem somewhat rough since the areas are large and the values of vibrotactile spatial acuity are rather small. Nevertheless, a thermal actuator (i.e. a Peltier cell) together with the heat sink has a square shape of 2.5 cm , and the minimum spacing between two of them is 5 cm . The experiment includes several tests with successive clearances up to 22.5 cm , aiming to assess the thermal spatial acuity thoroughly.

The results afford to determine how to create thermal stimuli as well. There are two possibilities:

- If the results are similar between the three areas, the thermal stimuli can be created in a generalised manner for every area of the vest.
- If there are significant dissimilarities between areas, the thermal stimuli must be customised depending on the area wherein they are applied.

Since most of the stimuli to render with the haptic vest are heating sensations, the experiments employ exclusively hot stimuli. Results are representative values to guide the distribution of thermal actuators, thus rerunning the tests using cold stimuli is only necessary if the perception is entirely defective. As in the case of the vibrotactile spatial acuity, the validation of the haptic vest proves if the distribution is adequate so that users perceive all thermal stimuli correctly (either hot or cold). Otherwise, the distribution may change to guarantee the optimal operation of the thermal actuation system.

The next sections present the materials for the experiment, the procedures, the statistical analysis, the results and the discussion about the whole experiment.

Figure 4-9. The cells are placed in all possible distances to conduct the experiments. They are attached with elastic tape to the cloth, and the cloth is attached to the vest through Velcro strips.

Materials

The Peltier cells are already described in Chapter 3, Subsection 3.3.3. The thermal system also includes the thermal sensor, even though its presence entails that the entire surface of the cell does not contact with the user's skin during the experiments. Nevertheless, the whole system avoids sudden and unwanted rises or drops of temperature caused by abnormal functioning.

The vest is the same used in the vibrotactile spatial acuity experiment. It allows an appropriate fit to the body due to the Velcro strips in the laterals. The three areas (RA, LA, and LB) also have two Velcro strips in order to attach the cloth with the Peltier cell.

The setup is composed of two clothes, and each one contains a Peltier cell. The cloths are made of polyester, and the cells are attached to them with elastic tape to maintain them immovable throughout the experiment. Each cloth further contains two Velcro strips to place them in the inner vest. Figure 4-9 shows two locations of Peltier cells in a phase of the experiment.

Experimental System

The experimental system is similar. An Arduino UNO controls the temperature rendered by both Peltier cells using the Arduino IDE. The general control system is a Dell Precision 490 Dual-Core Intel Xeon EM64t (graphics card nVIDIA®Quadro®FX 4500, 512 MB) running MATLAB to record participants' responses.

Participants

Participants were 25 volunteers: 15 males and 10 females ranging from 22 to 35 years old (mean $\pm$ SD, 26.58 ± 3.63 years). Participants were unaware of the purpose of the study. 20 participants were students of Universidad Politécnica de Madrid, whereas 5 participants were external from the institution.

Participants must be older than 18 years and younger than 40 years to avoid the influence of ageing on haptic perception [238] [239] [240]. A single participant indicated a neuropathology that could affect the sensitivity of the right side, and their results over the right areas were discarded. All participants who took part in the experiment provided written informed consent after the explanation of the whole procedure.

The Ethics Committee of Universidad Politécnica de Madrid approved the experimental procedures. The study complied with the Code of Ethics of the World Medical Association (Declaration of Helsinki).

Experimental Procedure

There are some aspects to consider before describing the experimental procedure. Firstly, the slowness of Peltier cells to reach whichever target temperature, even when using a PID controller. Participants were instructed to wait until the cell reaches the temperature to provide the corresponding response. Furthermore, the large size of Peltier cells hinders the placement of actuators at all test distances simultaneously. Only two cells are used throughout the experiment, even though they must be relocated between successive trials to test the perception at each distance.

The squared-shape of Peltier cells entails the orientation of thermal actuators can only be horizontal or diagonal. The definitive orientation is irrelevant since results provide the diameter of the thermal receptor field, owing to the spatial origin of stimuli is the same.

The procedure consists of several trials in which the thermal actuation system is placed at different distances and generates a hot stimulus on the side of the cells attached to the users' skin. When the side reaches the target temperature, it maintains for 3 seconds, and it cools down then. After this first phase, participants respond if they feel one or two thermal stimuli by pressing 1 or 2 in a numeric keyboard. Once the cell cools until the starting temperature, the heating process takes place anew, and the participant provides a second response to complete the trial.

The two main parameters of the experiment are the target and the starting temperature. The target temperature is set at $43^{\circ}C$ since it is below the pain limit ($45^{\circ}C$) and it is superior to the typical body temperature ($33-37^{\circ}C$); thus it is readily perceivable by users. Setting the base temperature at $28^{\circ}C$ allows the procedure to maintain permanent conditions with all participants.

Peltier cells are attached to a heat sink to dissipate the heat excess. The entire ensemble is square-shaped of 2.5 cm . Hence, the minimum distance between two ensembles is 2.5 cm , although, in that case, their sides would be adjacent, and users would perceive a single stimulus in all cases. In this manner, the minimum test distance is established at 5 cm .

According to the sizes of areas (RA, LA, and LB), the maximum distance between two Peltier cells is 22.5 cm . Then, the tested distances are steps of 2.5 , thus the possible distances to place the cells are as follows: $5, 7.5, 10, 12.5, 15, 17.5, 20$, and 22.5 cm .

As stated before, the setup uses only two Peltier cells which must be relocated before testing each distance. The participant has to take off the vest between trials, the experimenter changes the location of the actuators, and the participant wears the vest anew in order to begin the new trial.

Participants cannot see the location of both ensembles throughout the experiment. If they know the real location of both actuators, responses could be biased. For instance, if a participant sees the actuators placed at a considerable distance, they could believe they should perceive two different stimuli, and that previous thought might bias the response.

Results of the experiment are comprised then between 5 and 22.5 cm . Values are discrete and are given in 2.5 cm intervals, but they can provide an overall view rather dependable about the thermal spatial acuity to distribute Peltier cells over the areas of the vest.

Before beginning the experiment, participants perform two preliminary tests to become accustomed to the stimuli that they should perceive in the course of the experiment. Figure 4-10 shows a schematic of the whole procedure to ascertain the thermal spatial acuity.

In summary, the procedure consists of measuring the thermal spatial acuity at eight different distances. Participants have to complete eight trials per area to test all distances. Each trial contains two heating processes, obtaining two different measures. The complete procedure consists of 16 measures per area and 48 measures to finish the experiment wholly.

Statistical Analysis

Results of the thermal spatial acuity experiment allow for determining the distribution of thermal actuators over the haptic vest. Some statistical analyses are required to ascertain likely differences between the analysed areas or the sex of participants.

As in the experiment about vibrotactile spatial acuity, results are discrete values, and the statistical analyses are non-parametric tests since data do not follow a normal distribution. The specific tests hinge on the intended comparisons:

1. Comparison between all analysed areas. The most appropriate analysis is a Friedman test for related samples due to every participant completes the whole experiment over the three areas of the lower torso. If Friedman test shows significant results, it would be necessary to conduct a Conover post-hoc test to ascertain significant differences

Figure 4-10. The scheme shows the sequence of events that the participant must complete to finish the thermal spatial acuity experiment. The whole experiment lasts around an hour.

Figure 4-11. Values of thermal acuity for the three analysed areas. Each marker represents the median of all subjects in each area, and the error bars correspond to the IQR. The dashed line is the median of all spatial acuity values (15 cm), and the solid lines represent the IQR of the results $[13\ 17]\text{ cm}$.

between areas.

2. Comparison between results of males and females. The analysis is conducted using a Mann-Whitney test for non-related samples.

As the values are discrete, the mean and the SD are not the most suitable method to measure the central tendency of the thermal spatial acuity values. In such a manner, the most suitable option is the usage of the median to ascertain the central tendency, besides the IQR to ascertain the statistical dispersion of the results.

Results

The first step is to set the values of thermal spatial acuity for every analysed area. Figure 4-11 shows the values as a function of the three areas wherein the results are consistent all over the abdomen and the back. The dashed line corresponds to the median of the three values, whereas the solid lines indicate the IQR limits. Thereby, the median could be a representative distance to perceive two simultaneous thermal stimuli as different sensations.

Friedman test allows for comparing the three analysed areas (RA, LA, and LB). Results ($F = 0.29$, $p\text{-value} = 0.865$) show that there are no significant differences between the three areas and, thus, the post-hoc test is not necessary. These results are expectable since two areas have the same median, and the other value only differs 2.5 cm .

Lastly, the Mann-Whitney test ascertains likely significant differences between males and females, even though the results show equality as well (see Table 4.4).

Table 4.4
Results of the Mann-Whitney test for comparing thermal spatial acuity values
of males and females

Area	Statistic (F)	P-value
Right Abdomen	75.5	0.623
Left Abdomen	53	0.369
Lower Back	61.5	0.715

In summary, results of thermal spatial acuity are similar between all analysed areas and, hence, the distribution of thermal actuators may be uniform over whichever area of the lower vest.

Discussion

There are few references about experiments dealing with the thermal spatial acuity and, besides, they focus on researching the parameters over other body areas such as the hands or fingers [29] [40]. It is then difficult to make valid comparisons between these results and previous researches in other body areas, which further employs alternative methodologies to show the results (they use a percentage of success in distinguishing cold or warm stimuli) [40].

The experiment of thermal spatial acuity yields a median value of *15 cm*. That distance is an approximate value from which users begin to perceive two stimuli as two different sensations. This value is not accurate, and it hinges on each particular person, but it is a suitable value to distribute thermal actuators over the vest. Therefore, the median is the selected value to carry out the distribution of thermal actuators over the vest. If the distances are equal to *15 cm* or higher, users can perceive two different stimuli; otherwise, there is a risk of users perceive a single stimulus, even if the thermal patterns are not designed for that purpose.

Notwithstanding, the definitive distances for distributing the Peltier cells must hinge on the vibrotactile spatial acuity. The priority is the distribution of vibration motors since the distances are remarkably lower, but considering the required space for Peltier cells and the constraints owing to the dimensions of the haptic vest.

The uniformity of results is endorsed by the statistical analysis (Friedman test) whose values are above the significance limits. Although the experiment does not deem the upper areas of the torso, the resulting distances are high, and the distribution of thermoreceptors can be similar in the entire torso; thus, thermal actuators may be homogeneously distributed all over the vest (i.e. upper and lower areas).

Likewise, there are no significant differences according to the results of the statistical analysis (Mann-Whitney test) to compare the thermal spatial acuity between males and

females. This result is not unexpected since the lack of differences seems inferable because of the anatomy of the lower torso is somewhat similar between men and women.

Prior experiments about spatial acuity (both vibrotactile and thermal) seek to figure out differences about presenting stimuli using offset times between two consecutive presentations [29]. Nevertheless, this study solely considers a null offset time since most of the studies have demonstrated that the usage of non-simultaneous presentations reduces the spatial acuity values. Hence, if the distribution of actuators is conducted using the longest possible distance (i.e. the results of the experiment with null offset times), users do not have troubles to perceive two different stimuli.

Other psychophysical phenomena may affect spatial acuity and the distribution of thermal actuators. The most representative and unwieldy example is the spatial summation, even though diverse researches do not agree about their features and how it works [29] [241]. A workable solution in order to avoid the problem is to carry out the distribution of actuators at higher distances than the thermal spatial acuity values. However, there are reports about spatial summation phenomena with two distant actuators concurrently operating [242]. Hence, the distribution, according to the spatial acuity results, could prevent the phenomenon, but it cannot be completely assured.

The target temperature during the experiments ($43^{\circ}C$) is an aspect to consider carefully. The selection of that temperature lies in the haptic vest usually renders hot stimuli over users, being thus better to distribute actuators according to the thermal acuity values for hot stimuli. Nonetheless, those values could diverge when conducting the same experiments with cold temperatures ($15-17^{\circ}C$). Hence, it would be appropriate to repeat the procedure in the case the haptic vest was focused on rendering cold stimuli or if the perception is faulty when conducting the validation experiment (see Chapter 5). In any case, the configuration, according to this experiment, also allows for rendering cold stimuli, although the creation of cooling patterns needs to be accurately performed to avoid inappropriate or painful thermal effects.

4.3 Vibrotactile Absolute Thresholds

The experiment about vibrotactile spatial acuity serves to distribute the motors over the vest. The next step is to ascertain how to use those distributed actuators to create dependable haptic stimuli in the form of haptic patterns. To this end, it is required to study some psychophysical parameters related to vibrotactile feedback and the features of motors: the absolute thresholds and the upper and lower differential thresholds.

Absolute thresholds afford to settle the weaker vibration detectable by users (i.e. the lowest limit to create detectable vibratory stimuli). If a haptic pattern contains stimuli at lower intensities than the absolute threshold, it would be indiscernible, and users would not

receive all the information provided by the virtual scenario through the haptic vest.

It is essential to carry out this experiment firstly since these results are critical data to devise the experiment of differential thresholds. Otherwise, vibration motors could render non-detectable stimuli in the experiments about differential thresholds, biasing and becoming useless the subsequent results.

The experiment attempts to ascertain the absolute thresholds of all areas covered by the haptic vest. In such a manner, the creation of haptic patterns can involve any area so that stimuli are readily perceivable, discriminable, localisable, and relatable to events stemming from the VE.

Unexpectedly, the research about absolute thresholds over those areas is practically non-existent, due presumably to the dearth of haptic devices for the torso. Even so, there is some research about direct touch or forces (not vibrotactile feedback) [46] [47]; further, these studies are mostly focused on the hands [45]. As stated in Chapter 2, Section 2.2, most of the studies about haptic perception gear towards determining parameters for specific devices, but they do not ascertain psychophysical parameters which can be used generally.

The experiment has a significant difference as regards the experiments of vibrotactile spatial acuity since all areas, both of the front torso and the back, contain vibrotactile and thermal feedback. Thereby, the experiments to ascertain vibrotactile thresholds (both absolute and differential) are conducted in the 16 areas of the torso.

In such a manner, both experiments afford to characterise the entire torso, completing a haptic map of psychophysical parameters. Both thresholds, along with the vibrotactile spatial acuity, ease the creation of haptic patterns with any device that contains similar vibration motors.

Materials

The new version of the vest is divided into 16 areas: eight on each side of the body (6 areas on the front torso; 6 areas on the back; the right and the left shoulders; and the right and the left laterals). The areas are delimited by two Velcro strips to attach the cloth with the motors (see Figure 4-12).

The vest is made of neoprene since it is a flexible material which is further easily adjustable. The broad diversity of body sizes entails the necessity of tailoring several vests of diverse sizes to ease the wearability and the proper perception during the experiments. Therefore, there are two vests (S and L), even though the laterals and the shoulders have elastic fittings with Velcro strips to adapt them to the rest of standard sizes (i.e. M and XL, respectively).

Furthermore, the cloth for vibration motors is made of a rigid fabric to avoid the lateral spread of vibrations, seeking users to perceive all stimuli appropriately. The motors are sewn over the cloth instead of fitted in 3D frames, although the tautness of sewings maintains the

Figure 4-12. Areas in the front torso (left image), and the back (right image) of the vest for the vibrotactile absolute and differential thresholds experiments. The name of each area is written inside the rectangle. Those names are used for referring to those areas throughout the whole dissertation.

same conditions during the characterisation and the typical operation (see the green curve in Figure 3-9). Therefore, the voltage-frequency/amplitude relationship is the same than using the motor fitted in the frame.

There are three motors on the cloth at a distance of *10 mm* from each other to avoid permanent contacts (see Figure 4-13). During the experiment, the same motor is used to keep the conditions unchanging. Besides, the cloth has also two Velcro strips to affix it over any area of the subdivided vest.

Experimental System

The experimental system is similar to the one used for the spatial acuity experiments, consisting of the Arduino UNO driver to control, in turn, the PWM values which handle the intensity rendered by the motors. The system to manage all these components is a Dell Precision 490 Dual-Core Intel Xeon EM64t (using graphics card nVIDIA®Quadro®FX 4500, 512 MB) which runs MATLAB to record participants' responses.

Figure 4-13. Cloth with three motors attached by sewing. Only one motor is used throughout the experiment, whereas the rest are in the cloth to use them in case of malfunctioning or errors.

Participants

Participants were 22 volunteers: 10 males and 12 females ranging from 21 to 34 years old (mean $\pm$ SD, 24.652 ± 3.034 years). Participants were unaware of the purpose of the study.

As in the spatial acuity experiment, the age of participants must be in the range comprised between 18 and 40 years old due to the influence of ageing on haptic perception [238] [239] [240]. Before starting the experiment, participants were asked about diagnosed neurological issues, medication, psychological problems or diseases which might affect haptic perception [243] [244]. Participants who did not refer troubles were selected to take part in the experiment.

All participants took part voluntarily in the experiments and provided written informed consent. The Ethics Committee of Universidad Politcnica de Madrid approved the experimental procedure. The study complied with the Code of Ethics of the World Medical Association (Declaration of Helsinki).

Experimental Procedure

The objective is to measure the absolute vibrotactile thresholds in the 16 areas of the torso. Results afford to ascertain whether thresholds are similar, or there are differences between areas. Moreover, those results serve to determine the necessity for customising haptic patterns for every individual area (in the case the results show significant differences) or, contrarily, if patterns can be developed in a generalised manner (if the results do not show significant differences).

A participant took 5 hours and 30 minutes to complete the experiment in the 16 areas of the vest. The time is overly long, and it is quite intricate for a participant to finish the whole experiment. There were then two options: completing all areas in several sessions or completing only a single session. The sessions lasted 1 or 2 hours in all cases to avoid extreme fatigue. Participants completed approximately three areas per hour with a break of 3-5 minutes between areas to reduce the fatigue and not reduce concentration.

The configuration of the experiment entailed the need for a high number of participants to complete the 16 areas since the majority of participants completed a single session. Even so, the usage of data from several participants does not affect the results. The procedure is robust enough to ensure the validity of the gathered data despite the same participants did not complete the whole experiment.

The procedure used a two-interval forced-choice (2iFC) task composed of two intervals with a duration of 350 milliseconds each one, besides a temporal gap of 1.3 seconds between them. One of the two temporal intervals contained the test vibration, whereas the other interval contained a void stimulus (no vibration). Both stimuli were assigned randomly to both intervals. Participants had to discern what interval contained the vibratory stimulus by pressing the number 1 or 2 on a numeric keyboard. After the system recorded the participant's response, it started a new trial.

The frequency of the test stimulus changed in each trial. The specific value was determined according to a Bayesian adaptive staircase [245] [246] [247] whose prior distribution of frequencies was uniform (i.e. non informative about the threshold value), the model function was the Logistic (see [248] and [249] for supplementary information) (the parameters were guess rate = 0.5, lapse rate = 0.01, delta (δ) = 0.0123, and sigma (σ) = 0.8). In order to update the staircase after the participant's response given in each trial, the posterior distribution is calculated according to equation 4.1. In that equation, P is the posterior distribution, and M is the model function, $C = 1$ and $I = 0$ after a correct response, and $I = 1$ and $C = 0$ after an incorrect response. The number of trials is n . The frequency presented in each trial was obtained from the mean of the posterior distribution $\theta_i = \bar{P}_i(x)$.

$$P_{i+1}(x) = P_i(x)M(x, \theta_i)^C [1 - M(x, \theta_i)]^I, i \in [1, n] \quad (4.1)$$

The final estimation of the threshold was the mean of the final distribution after completing 40 trials ($n = 40$) ($P_{n+1}(x), n = 40$). In this manner, the absolute threshold is defined as the minimum intensity required to detect a vibratory stimulus with a success rate of 75 %.

The Bayesian staircase allows the convergence of temporal frequency values with the previous success rate. Participants could even respond to some trials randomly, but the robustness of the procedure ensures the reliable ascertainment of absolute thresholds. The number of trials was estimated and fixed at 40 in order to ensure the convergence of the

staircase.

The experiment seeks to determine the minimum vibratory intensity required so that participants can perceive the stimulus when the vibration motors are attached to the vest. Therefore, the stimuli presented were close to that low limit, and participants could not perceive some stimuli during the experiment. Participants were then advised that they had to press a random key to continue the experiment in those cases.

The complete measurement of an area consisted of 3 individual measures of the threshold per participant, whereas the final absolute threshold was the mean of those three measures. Thereby, 48 measures were needed to obtain 16 thresholds (one per area). Every measure was obtained after the completion of the staircase of 40 trials. A total number of 5 different participants for each area were required to obtain meaningful results, which implied 240 staircases to finalise the utter experiment. Figure 4-14 shows a schematic of the whole procedure in a session to ascertain a single absolute threshold.

Regardless of the participant completed the whole experiment or only a part; the tested areas were random. If haptic perception does not change within the range comprised among 18 and 40 years old, the distribution of participants per areas could be random without risk of biases in the final results.

This experiment and the next one employ a similar process to determine the voltage to apply in every trial by using the voltage-frequency curve obtained in the characterisation. An example is illustrated using this experiment: the first frequency rendered by the motor could be, for instance, 80 Hz which corresponds to a voltage of 0.71 V , so the driver applied a PWM signal of 10 % duty cycle. If the user identified the vibration rightly, the driver system rendered a superior value in the next trial (e.g. 93 Hz after applying 4.1), which corresponds to 0.81 V and a PWM signal of 11 % duty cycle. The procedure is similar during the risings and falls of frequency throughout the 40 trials of each experiment.

There are some standard features between this procedure and the experiment of differential thresholds (see Section 4.4). Those features state henceforth, but they are applicable for the next experiment as well.

Participants had to wear the same kind of undershirt to maintain the experimental conditions for every participant. They selected and wore a shirt of its regular size (S, M, L, or XL); then, the experimenter placed the cloth over a random area of the vest, and participants wore the vest afterwards. The vest must be tight to remain the motors attached to the participants' skin, providing that they had to feel entirely comfortable during all the process.

A pure tone of 800 Hz appeared to point out the presentation of every stimulus as well as preventing participants from distractions. The tone was also presented during the void stimulus to highlight the instant wherein the stimulus should appear.

Lastly, participants heard white noise, using headphones, in order to mask the sound of

Figure 4-14. The scheme shows the sequence of events to complete by the experimenter and the participant to finish both experiments. There is a unique difference between procedures for absolute and differential thresholds. In the case of the absolute threshold, the interval contains the void stimulus or the test vibration; whereas the interval contains a reference or a test vibration in the differential thresholds experiment.

Figure 4-15. Values of vibrotactile absolute threshold for the sixteen analysed areas. Each marker represents the mean of all subjects in each area. The dashed line is the mean of all absolute threshold values (69.1074 Hz), and the solid lines represent the 95% confidence interval of the mean $[67.5802\ 70.6346]\text{ Hz}$.

the motor's vibration. The noise was only reproduced during the presentation of the stimuli not to bother participants, and it stopped during the gaps. Moreover, the volume was adjusted at the beginning to avoid discomfort, providing that the sound of motors remained masked.

Statistical Analysis

After concluding the experiments, the statistical analysis of the results affords to ascertain likely differences between the analysed areas. Statistical results are used to determine if every area has an absolute threshold or it is suitable to select a single value in order to create haptic patterns in all areas.

Due to the lack of awareness about the variance of the results, the analysis is an unequal variance One-Way ANOVA for independent measures (Welch's ANOVA). If the previous test shows significant differences, it would be needed to carry out an unequal variance t-test (Welch's t-test) to determine the difference between specific areas. The same t-test is used to determine likely differences between right and left areas of the vest.

Results

The experiment yields 16 absolute thresholds corresponding to every area of the haptic vest. Figure 4-15 shows the thresholds (in Hz) as a function of the analysed areas. The minimum value is 64.5103 Hz that corresponds to the Upper Right Front (URF), whereas the maximum value is 75.7229 Hz that corresponds to the Lower Right Front (LRF).

Table 4.5
Results of the Welch’s t-test comparing vibrotactile absolute thresholds of the right and left areas

Comparison	t’	P-value
Right Shoulder (RS) vs. Left Shoulder (LS)	1.223	0.2391
Upper Right Front (URF) vs. Upper Left Front (ULF)	1.1486	0.2743
Medium Right Front (MRF) vs. Medium Left Front (MLF)	0.1379	0.8926
Lower Right Front (LRF) vs. Lower Left Front (LLF)	0.8566	0.4036
Upper Right Back (URB) vs. Upper Left Back (ULB)	0.3429	0.7357
Medium Right Back (MRB) vs. Medium Left Back (MLB)	-0.5091	0.6171
Lower Right Back (LRB) vs. Lower Left Back (LLB)	-0.0818	0.9357
Right Lateral (RL) vs. Left Lateral (LL)	-0.1105	0.9133
Right Back vs. Left Back	0.3978	0.6919
Right Front vs. Left Front	-0.2208	0.8259
Right Areas vs. Left Areas	0.0893	0.929

Welch’s ANOVA test shows that there are no significant differences between areas ($F = 1.191$, $p\text{-value} = 0.306$). Thus, it is suitable to consider the absolute vibrotactile threshold as a constant independent on the area of the vest. The average value of all absolute thresholds is the reference in order to set a single absolute vibrotactile threshold. The value is 69.1074 Hz, whereas the 95% confidence interval of the mean is $[67.5802\ 70.6346]$ Hz.

Finally, some additional Welch’s t-tests show that there are no significant differences between distinct areas of the vest, endorsing the results of Welch’s ANOVA (see Table 4.5). The conducted comparisons are as follows:

- Individual comparison between all right and left areas (Right Shoulder - Left Shoulder, Upper Right Torso - Upper Left Torso, et cetera)
- Comparison between all right and all left areas of the front torso (Lateral, Upper Torso, Medium Torso, and Lower Torso).
- Comparison between all right and all left areas of the back (Shoulder, Upper Back, Medium Back, and Lower Back).
- Overall comparison between all right and all left areas

Discussion

The main finding of this experiment is the absence of a relationship between thresholds and areas (the values are similar in the entire torso). Statistical analysis shows that there are no significant differences between individual areas, but neither between right and left areas, according to Welch’s t-tests conducted.