Technische Universität München
Lehrstuhl für Ergonomie

Master Thesis

Evaluation of Acceleration Sensation induced by Proprioception on a Motorcycle Simulator

Evaluierung der durch Propriozeption induzierten Beschleunigungswahrnehmung auf einem Motorrad-Simulator

Antonio Doz Nadal

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Master Thesis

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Module: Automotive and Combustion Engine Technology

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"*Life is not what one lived, but what one remembers*

and how one remembers it in order to recount it"

Gabriel García Marquez (1927-2014)

To my parents and sister

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Abstract

This master thesis was carried out to solve the lack of a mechanism to represent long-term accelerations in motorcycle simulators. It proposes a construction, named G-Vest, specifically designed to stimulate the somatosensory system.

The G-Vest is capable of simulating acceleration effects by producing pressure variations to activate the mechanoreception and proprioception. The prototype consists of a vest actuated by electric motors, which create a force backwards. The system can be easily integrated into a motorcycle simulator, like the one at BMW Motorrad. This work carries out a research study to prove the functionality of the G-Vest.

Twenty participants conducted a study in which they reproduced three accelerations up to a velocity of 50, 100 and 150 km/h and a free ride with and without the G-Vest active. The results induced by the G-Vest show that the inertial and airflow-induced forces can be represented by a surface pressure on the torso and the perception of acceleration is realistic without exciting the vestibular system. Besides, the comfort of the G-Vest and the guaranteed freedom of movement on the motorcycle are also noteworthy.

This work opens up a new avenue of investigation where the G-Vest is the starting point in the representation of long-term accelerations on motorcycle simulators.

Keywords: Motorcycle simulator, perception of acceleration, mechanoreception, proprioception, G-Vest.

Zusammenfassung

Die Vorliegende Untersuchung wurde durchgeführt, um das Problem zu beheben, dass langfristige Beschleunigungen in Motorrad-Fahrsimulatoren nur unter hohen Kosten dargestellt werden können. Sie schlägt eine Konstruktion namens G-Vest vor, die speziell entwickelt wurde, um das somatosensorische System zu stimulieren.

Die G-Vest kann Druckschwankungen erzeugen, um die Mechanorezeption und Propriozeption zu aktivieren und so einen Beschleunigungseffekt zu simulieren. Der Prototyp besteht aus einer Weste, der von Elektromotoren angetrieben wird und eine Kraft erzeugt, die entgen der Fahrtrichtung zieht. Das System kann mit geringen Aufwand in einem Motorrad-Fahrsimulator integriert werden, genauso wie für den BMW-Motorrad Simulator geschoben. Diese Arbeit hat zum Ziel, eine Probandenstudie durchzuführen, um die Funktionalität der G-Vest unter Beweis zu stellen.

Zwanzig Probanden haben drei virtuelle Beschleunigungen von 0 km/h bis 50, 100 bzw. 150 km/h und eine freie Fahrt auf einer Landstraße mit und ohne eine G-Vest durchgeführt. Die Ergebnisse zeigen, dass die Trägheitskraft in Fahrtrichtung und die Windlast durch Flächenkraft auf den Oberkörper durch die G-Vest dargestellt werden können und die Beschleunigungswahrnehmung ohne Anregung des Gleichgewichtsorgans realitätsnah ist.

Dadurch wird eine neue Forschungs und Entwicklungsrichtung aufgezeigt, wie langfristige Beschleunigungen in Motorrad-Fahrsimulatoren darstellbar sind.

Schlüsselwörter: Motorrad-Fahrsimulator, Beschleunigungswahrnehmung, Mechanorezeption, Propriozeption, G-Vest.

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1 Introduction

The history of simulators stems from the second half of the 20th century (Blana, 1996). At the beginning, they were developed in the aeronautic field as a tool for training novice pilots in a safe environment. The success known in this area has motivated an extension of this technology to other types of vehicles, initially cars and recently also motorcycles (Hima and Arioui, 2008). Even so, the sophistication found in aircraft and aerospace simulators has not presently been applied to other vehicles such as motorcycles (Letovsky and Fried, 1991).

Motorcycle simulators can be used in a field ranging from a study of the consequences of driving under the influence of alcohol (Colburn and Edwin, 1993) to the design of new commercial motorcycles (Ferrazzin et al., 2003). However, such simulators are not capable of providing a realistic simulation of all the forces and movements experienced when riding (Chiyoda and Sugimoto, 2002). Although they have undergone a continuous development, it is certainly true that there is still a lack in the simulation of long-term accelerations. But what is exactly meant by long-term accelerations? In this thesis they are defined as accelerations that cannot be reproduced by a motion platform any more due to mechanical limitations. This classification helps to categorize different systems and take account of technical limitations, like the travel of actuators.

1.1 State of the art, prior works and motivation

Over the last few years, several motorcycle simulators have been built (Ferrazzin et al., 2001), (Hima and Arioui, 2008) or (Cossalter and Stefano, 2010). However, the simulation of long-term accelerations has been a weak spot. There is no general solution to represent inertial and airflow induced forces due to many difficulties, such as the mechanical speed limitation or the lack of space in a motion system.

One of the major difficulties that must be faced is the reproducing of a feeling of acceleration without doing the usual movements. Some works propose systems which provide long-term accelerations stimulating only the visual system and one of the other two channels (somatosensory and vestibular system) that the human body uses to perceive the acceleration (Born, 1989). Therefore, the lack of any study related to the stimulation of the somatosensory system for this purpose limits the scientifically proven use of this type of system.

The aim of this thesis is the construction of a system to represent long-term accelerations based on the aforementioned works in cooperation with TU Damstadt and WIVW within the DESMORI framework (Hanselka, 2014) (Anton, 2015). The thesis conducts a research study to prove the functionality of the system and allows to evaluate and decide if it is the right direction in the simulation of long-term accelerations.

Figure 1-1 shows the working principle of the system, named G-Vest, that tries to simulate an inertial volume force and the airflow-induced forces by applying pressure on the torso. It consists of a vest actuated by electric motors, which creates a backwards force and produces pressure variations on the torso of the participant.

The construction of the G-Vest must comply with the following requirements:

- Maximal contact surface between the vest and the participant in order to distribute the force of the motors and avoid punctual pressures.
- High comfort for the participant
- Integration in the motorcycle simulator

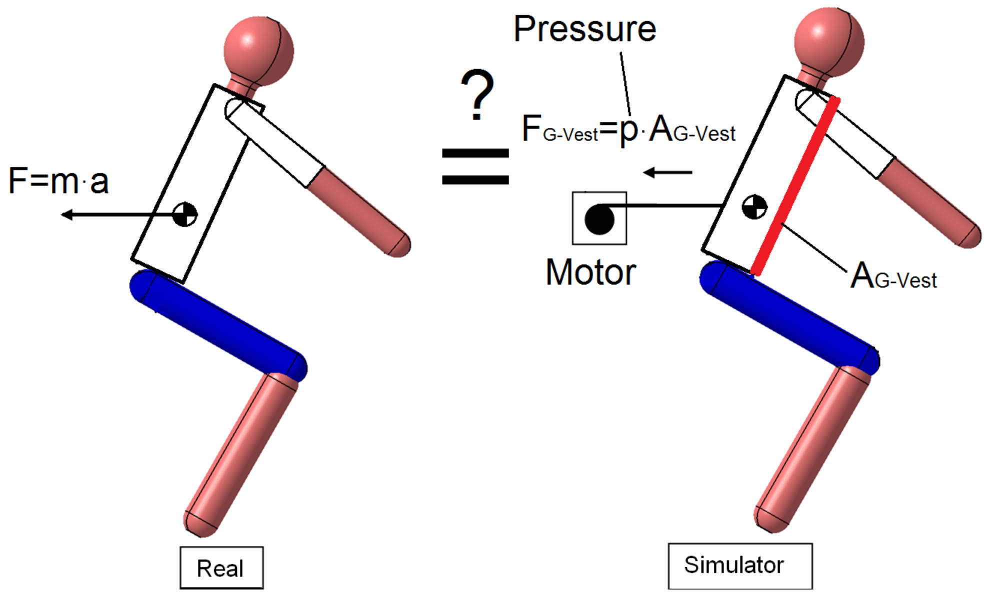

Figure 1-1.: Working principle and sketch of the G-Vest

Once the G-Vest is built, a specific control is developed. The G-Vest simulates the inertial and the airflow-induced forces that depend on the acceleration and velocity of the rider.

After the construction and integration of the G-Vest, the main aim of this project is to prove and validate the functionality of the system to simulate long-term accelerations. This section consists of a research study with the objective to investigate the differences between driving the simulator with and without the G-Vest in order to answer the question whether the long-term accelerations are realistically reproduced by this system. The study focuses on the following hypotheses:

- The inertial force during riding a motorcycle can be represented by surface forces on the torso
- The airflow-induced forces during riding a motorcycle can be represented by surface forces on the torso
- The perception of acceleration riding a motorcycle is realistic without stimulating the vestibular system
- The rider's freedom of movement with the G-Vest is guaranteed
- The G-Vest is comfortable

Therefore, the principal objective of this thesis is to open a new path to simulate long-term accelerations in motorcycles simulators.

1.2 Work structure

This section describes the structure of this thesis as shown in figure 1-2. After the introduction, chapter two describes the theoretical foundations needed to understand the presented main concepts. This one is divided into three sections and explains the human perception of acceleration, the currently available systems to represent it and a review of motorcycle simulators throughout history.

Based on the theoretical knowledge explained in chapter two, the idea of the G-Vest is explained in chapter three. Chapter four clarifies the construction of the G-Vest and the design of the control system required to command it.

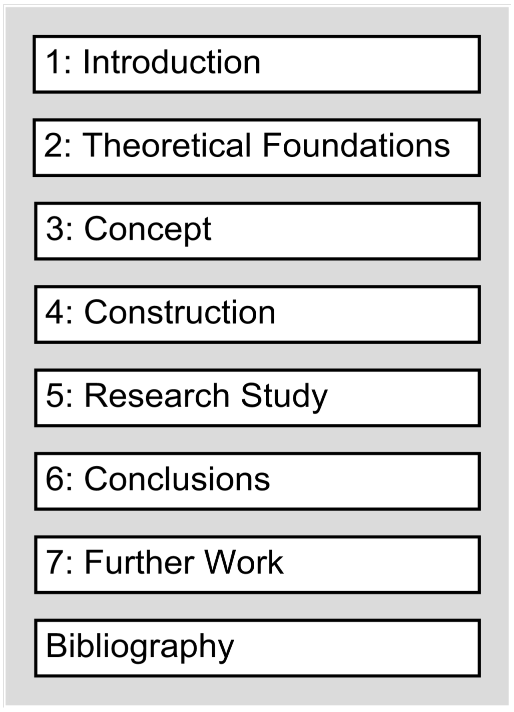

Figure 1-2.: Structure of the thesis

Once the G-Vest is built and integrated, all the information about the research study can be found in chapter five. This section explains the hypotheses followed, the used method and concludes with the results of the study and a discussion about them.

Chapter six presents the conclusions, which are found after completing the whole task. The thesis finishes at Chapter Seven, that describes the further work to continue with the development.

2 Theoretical Foundations

As mentioned in the introduction, this chapter contains the necessary theoretical foundations to understand the concepts developed in the following sections. It is divided into three main sections, where the first one provides information to understand the human perception of acceleration. The correct systems to reproduce accelerations in different simulators are presented in the second part and the chapter concludes with a review of motorcycle simulators throughout history and the solutions that have been developed so far.

2.1 Human's perception of acceleration

Perception interprets the constant *stimulus* that the human body receives and the receptors process (Goldstein, 2008). The human motion perception is a sensor data fusion of different sensory organs. The following enumeration gives an overview of the sensors that are involved in the awareness of humans' movement (Jochen and Sammet, 2006):

- Auditory system (for listening)
- Visual system (for seeing)
- Somatosensory system (deformation of the skin, feeling of pressure)
- Vestibular system (equilibrium organ)

The most important information about the body's state of motion is the integration of the information based on the vestibular, somatosensory and visual system. Moreover, it is complemented by the auditory system (Goldstein, 2008). Fast high-frequency motion changes are better recognized by the vestibular and somatosensory systems than through visual perception (Distelmaier and Dörfel, 1983).

The next pages explain the basic concepts about the perception of acceleration through the vestibular and somatosensory systems (proprioception and mechanoreception). Before describing how a subject perceives acceleration, the basic concepts about the psychology of perception must be explained, in order to understand how humans arise this from the information that the sense organs send and the neurology system converts (Goldstein, 2008).

2.1.1 Psychology of perception

Everything seen, heard, tasted, felt or smelled is created by the mechanisms of the senses (Goldstein, 2008).

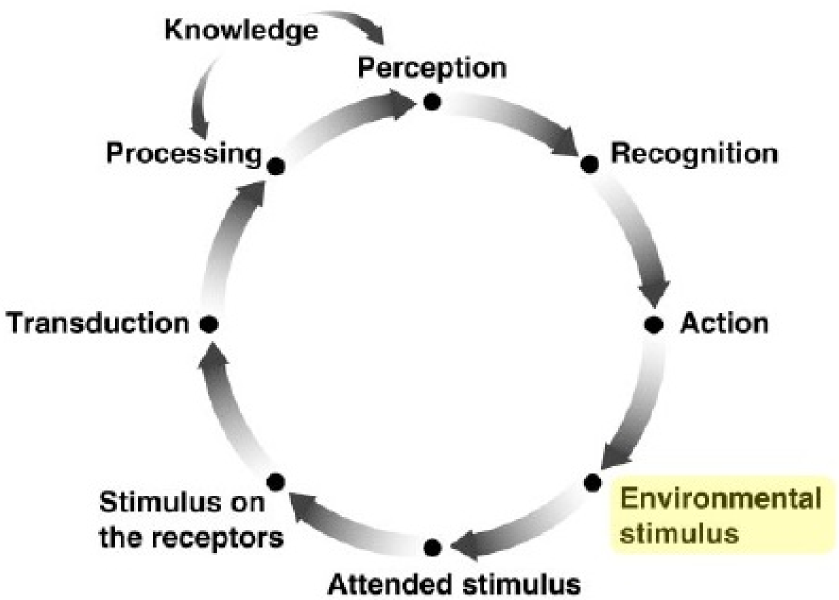

Figure 2-1.: The perceptual process (Goldstein, 2008)

Figure 2-1 shows the perceptual process, which begins with a *stimulus* in the environment and ends with the conscious experiences of perceiving something, recognizing it and taking action with regard to the recognized element. It is important to emphasize that this is only a simplified version of what actually happens. The process of bringing information from the outside world into the body and to the brain is called sensation and is a passive procedure, whereas perception can be defined as the active process of selecting, organizing and interpreting the information brought to the brain through the senses (Alley, 2015). It should be made a difference between perception and recognition, as it can be understood from this simple example: perception means "I see something" whereas recognition signifies "That is a tree" (Goldstein, 2008: 3). These two things may not always happen one after the other, but can happen at the same time or even in reverse order. Everything a person perceives is not based on direct contact with *stimuli* but on the reactions that are detected by the receptors and on the person's nervous system activity (Goldstein, 2008).

The problem appears when it is time to decide which information is the most important. The human being has a selective attention, strongly influenced by motivation. Not to mention that the way humans perceive the world is a function of their past experiences, culture, and biological make up. Previous experience, knowledge and expectation in addition to the *stimulus'* information, are used to build it. For example, a painting can be watched and not really understood the message the artist tried to convey. But, knowing about it, there are things in the painting that unable to be seen before (Alley, 2015). That is the reason why the perception system is not infallible and can perceive illusions, defined as something that deceives us by producing a false impression of what is real. The perception systems are not static and are subjected to continuous learning (Goldstein, 2008).

2.1.2 Somatosensory system

Mechanoreception and Proprioception

The somatosensory system is the part of the sensory system concerning the conscious perception of touch, pressure, pain, temperature, position, movement, and vibration, which come from the muscles, joints or skin, considered to be our largest sensory organ (Gleveckas-Martens, 2013).

This system can be subdivided into five subcategories as outlined below: mechanoreception, proprioception, thermoreception, nociception and veszeroception (Treede, 2011). These subcategories use two different pathways: the lemniscal and the spinothalamic. The first one is shared by mechano- and proprioceptive receptors and it carries information that require the transmission to be fast and precise. The second pathway carries information that does not require the transmission to be as fast and precise: it carries pain, hot, cold, and sexual sensations (Bhatnagar, 2002).

The following section explains in more detail the mechanoreception and proprioception concepts. Thermoreception, nociception and veszeroception are out of scope of this project due to their lack of importance to the developed work, and hence they are not explained. However more information about them can be found in these sources: (Treede, 2011) (Goldstein, 2008).

Mechanoreception

Mechanoreception is a widely distributed sensor modality that conveys the qualities of pressure, contact, vibration and cutaneous tension (Rupert, 2000) (Treede, 2011). Through different types of receptors, which have different adaptation speeds, we are allowed to detect a wide variety of features, from the recognition of object's spatial details to the detection of vibration going through the localization of tactile *stimulus* and their direction.

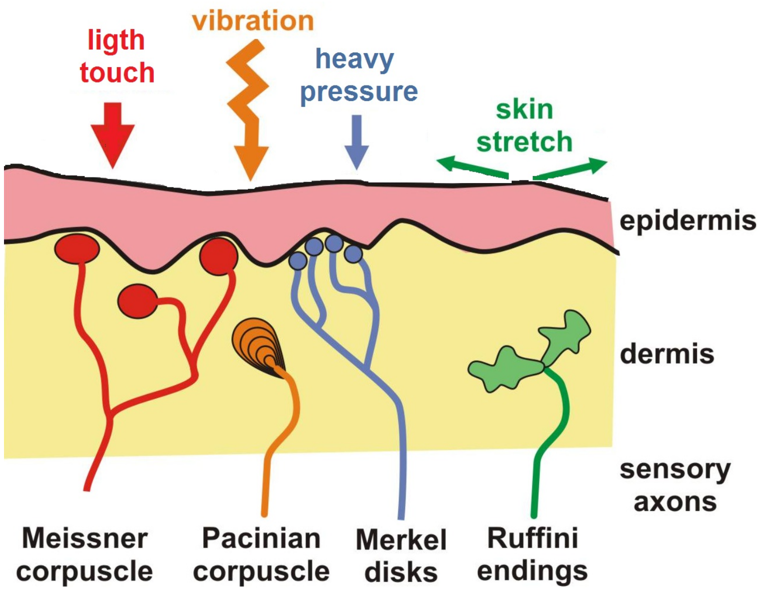

Figure 2-2.: Mechanoreceptors in the skin (Verpillot, 2012)

To be capable of feeling these things, the human skin is provided with many of mechanoreceptors shown in figure 2-2. Meissner corpuscle are rapidly adaptive receptors and are responsible for sensibility to light touch. The Merkel disks provide information on pressure, position, and deep static touch features such as shapes and edges. The Ruffini ending is sensible to skin stretch. And Pacian corpuscle are responsible for sensitivity to vibration and pressure (Bear et al., 2007).

Proprioception

The proprioception is a self awareness that enables the detection of the position, direction of motion, acceleration and strength of the body and limbs (McCloskey, 1978). The body position is perceived both at the conscious and unconscious level. The conscious proprioception gives information to facilitate complex motor activity, while the data of unconscious proprioception is used to coordinate basic posturing during sitting, standing and simple gait activities. Proprioception is based on a multi-component sensory system which includes: various types of peripheral receptors which can detect specific signals and major sensory afferent pathways, which carry the information from the spinal cord up to the cortex (Johnson and Soucacos, 2008).

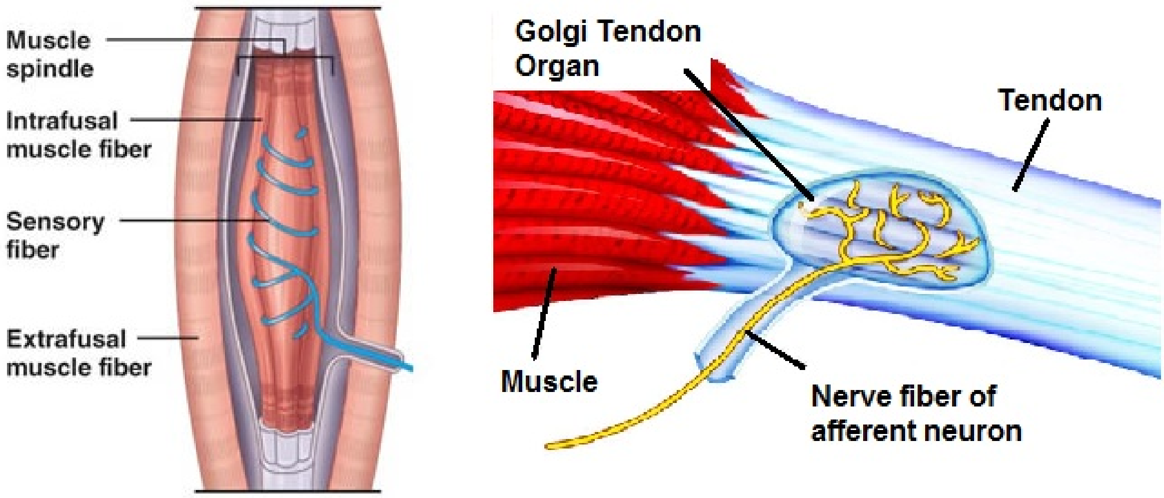

Figure 2-3.: Left part: Ruffini receptor. Right part: Gogli receptor (Pearson, 2011)

The relative position of our skeletal body parts is determined by the angles of our joints (Burgess et al., 1982). This information is provided by receptors specialized in detecting the degree of stretching of the muscles and tendons. In the joint capsule there are many Ruffini corpuscles which are stimulated by the movement of the joint. These receptors can be seen on the left part of figure 2-3. In tendons, there are also specialized receptors, known as Golgi tendon organs. These are shown in Figure 2-3, where it can be seen that the muscle fibres are in the upper part, whereas the tendon is in the lower part bound by the Golgi tendon organ, which consists of multiple nerve branches interlaced with elastic collagen fibrils. Stretching of the tendon stimulates afferent nerve fibres that transmit information to the spinal cord. There are different types of receptors that respond to different angles of rotation of the joint (Goldstein, 2008).

There are two types of muscle spindles that give information about the static position and also contribute to the kinesthetic sense of position and movement (Johnson, 2010).

The state of stretch or contraction of the muscle is relayed to the spinal cord and then to the brain, where two different body schemas are represented. The first one codes the orientation of the body parts in space and time, while the second one represents the structural description through the codification of the position of each body segment.

2.1.3 Vestibular system

The vestibular system is the sensory system that detects motion of the head in space and stabilizes the visual axis maintaining head and body posture (Cullen and Sadeghy, 2008). In addition, it provides the subjective sense of movement and orientation of the body in regard to gravity (Day and Fitzpatrick, 2005). The vestibular sensory organs are located in the petrous part of the temporal bone in close proximity to the cochlea, the auditory sensory organ, and it is redundant at the left and right side. It is comprised of two types of sensors: the two otolith organs which cover the saccule and utricle and the three semicircular canals (Goldstein, 2008).

The otolith organs consist of the saccule and utricle, which detect the direction and magnitude of gravity, as well as transient linear accelerations due to movement cited by (Cullen and Sadeghy, 2008). The semicircular canals are a set of three arranged in three orthogonal planes, which are sensitive to the angular rotation and the head speed (Naunton, 2012).

2.1.4 Perception of acceleration on a motorcycle

The previous subsections explained both the somatosensory and vestibular system, which provide the acceleration sensation in humans. However, the perception of position, motion and acceleration of body parts does not work independently; it comes from the integration of concordant and redundant information from the four systems: somatosensory, visual, vestibular and auditive system. These pieces of information converge and are recognized to contribute to controlled movement (Rupert, 2000). However, the visual and auditive system is not described in this work, because they are two of the inputs that are always used in simulators and it has already been covered in many other works (Brandt et al., 1973).

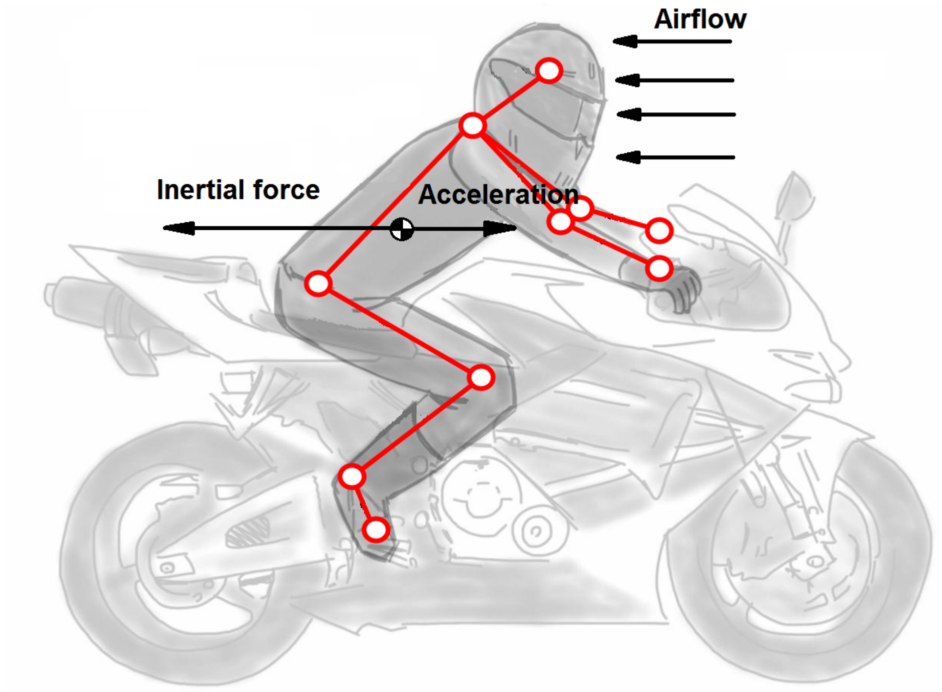

Figure 2-4.: Inertial force and airflow during riding a motorcycle

In short, during the operation of riding a motorcycle these four systems are receiving information about the environment and the forces acting on the rider. The vestibular system detects the linear acceleration through the otolith organs when driving straight, whereas, the semicircular canals detect the angular speed when approaching a turn with the motorcycle. The perception of acceleration is corroborated by the information that comes from the somatosensory system. The proprioception detects the inertial force due to accelerations. It detects acceleration through the position of joins and the degree of stretching of the muscles and tendons in order to not fall down during an acceleration or deceleration. The airflow produces a pressure on the rider, that helps him to know about the velocity. The mechanoreceptors are responsible for detecting this pressure.

Finally, as read in 2.1.1, the past experiences help to perceive all these signals and recognize them as an acceleration.

2.2 Acceleration simulation systems

The following section explains the systems used in the representation of acceleration in a simulator. As said above, the perception of acceleration is the integration of information from these three systems: somatosensory, visual and vestibular. Assuming the visual system is always activated by the visual cue present in all the simulators, this section focuses on the system that stimulates the other two. The basic characteristics of the machine are explained as well as the type of acceleration that it can provide and the system that becomes excited.

Hexapod

An hexapod or Stewart Platform is a motion device with six degrees of freedom (DOF): heave, sway, surge, pitch, roll, and yaw (Lothar, 1999) that can be used to provide accelerations in a riding simulator.

As seen in figure 2-5 there is a fixed part mounted to the ground (1), acting as the base, and a moving part (2) where the mock-up (a working model of a machine or structure like a motorcycle for a simulator) can be placed. This mock-up part (2) moves with the person and activates the vestibular channel. The saccula and utricula are excited by accelerations in a linear direction, whereas the semicircular canals react to the rotational speed of the platform. All these signals are sent to the brain, that interprets them as accelerations.

Figure 2-5.: Hexapod: a 6 DOF Motion Platform (1 base, 2 top plate, 3 actuators) (Ckas, 2015)

Figure 2-5 shows all the parts of the hexapod. The joint between the base and the top plate is made with six actuators (3), which are mounted in pairs to the mechanism's base, crossing over to three mounting points on the top plate. The length of these links can change, offering the controllability of the six DOF. Figure 2-5 shows an electric platform with crank arm motion systems. However, the actuators can also be hydraulic or pneumatic and there is a broad range of different types of actuators and sizes, depending on the field of application (Lazarevic, 1997).

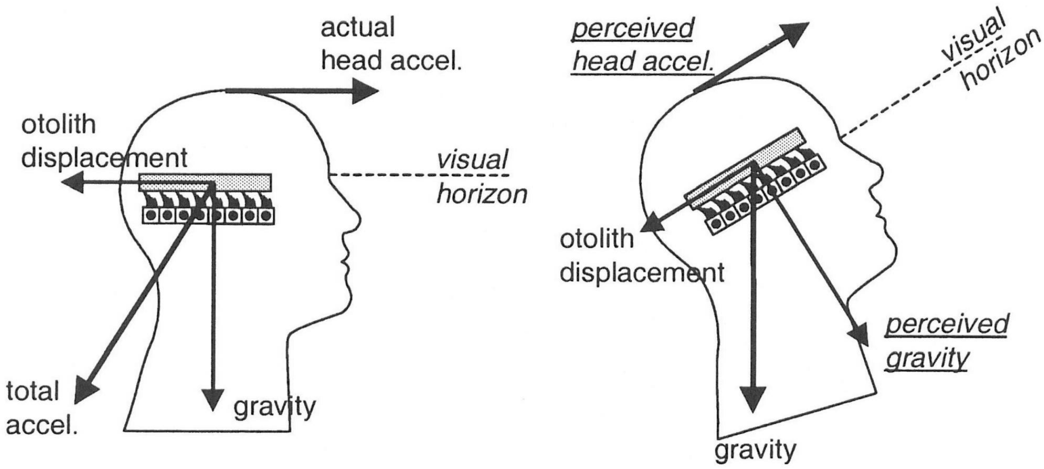

Figure 2-6.: Tilt-Coordination: Simulation of a long sustained acceleration rotating subject head (Weiss, 2006)

The hexapod is used at present to simulate both short- and long-term accelerations, although long-term are not realistically reproduced (See figure 3-1). Long-term accelerations can be simulated using a method called tilt-coordination (see figure 2-6). For this effect the participant must not has any external spacial reference. When he is tilted, his brain can interpret a part of the gravity force as an acceleration in a linear direction. This method has two problems: the first one is the maximal rotation speed (3°/s) and the second one is the maximal angle before the person realizes about the inclination (20-30°). These values limit the accelerations that can be simulated. An explanation of tilt-coordination can be read in (Fischer, 2009).

G-Seat

A G-Seat was originally designed to be used in aircraft simulators and it provides long-term accelerations without moving the participant.

In a real flight, when accelerating the plane the pilot is pressed to the seat and in the simulator the G-Seat presses the participant to have the same experience and to simulate accelerations.

The G-Seat shown in figure 2-7 contains two mosaics of air cells (1) forming a back (2) and a seat cushion (3), which have a rigid top plate. The top plates of the cells in each mosaic form the body supporting surface of the corresponding cushion. The cells may be individually driven under computer control to vary the elevation, attitude and shape of these body supporting textures.

By selectively controlling and coordinating each cell, the elevation can be varied, as well as the attitude and change of these body support, producing pressure gradient variations. These variations stimulate the somatosensory system, both the mechanoreception and the proprioception. On the one hand the Merkel disks are excited by the gradient pressure and give the information about it. On the other hand the Ruffini receptor gives the information about the degree of stretching of the muscles, which are tense due to this pressure (Cardullo and Kron, 1976).

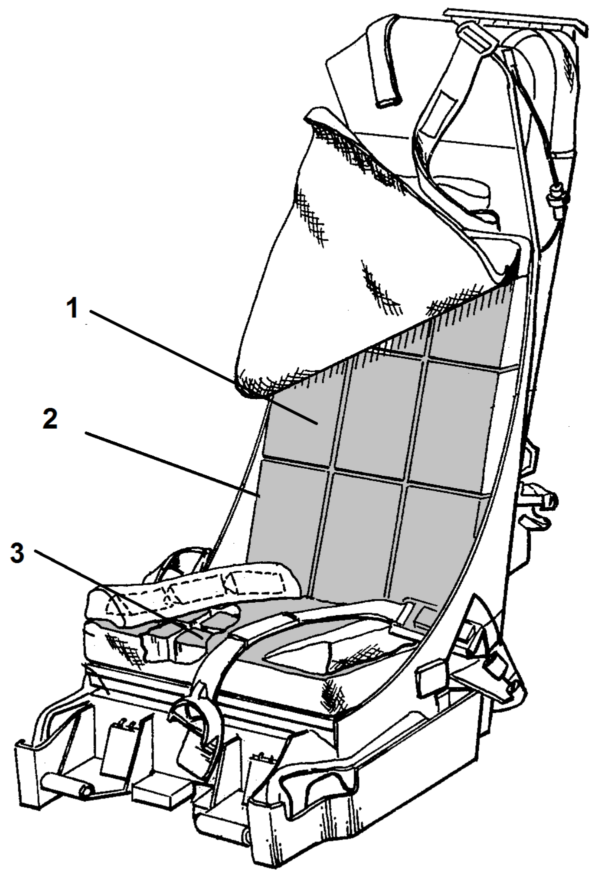

Figure 2-7.: G-Seat construction (1 air cells, 2 back cushion, 3 seat cushion) (Cardullo and Kron, 1976)

Galvanic Vestibular System (GVS)

The Galvanic stimulation is a new system in development phase that can be used to simulate long-term accelerations without moving the participant in all kind of simulators.

The functioning of the system is based on electric shocks. It provides pulses of electric shocks that stimulate the vestibular system. The participant perceives these *stimuli* of the Saccula, Utrila and semicircular canals as accelerations or rotational speeds.

The Galvanic stimulation, shown in figure 2-8, includes at least three different sets of electrodes (1) that are located on the human subject connected to an electrical stimulator. Stimulation passes between at least two electrodes of each distinct set. Anodal and cathodal GVS affect the discharge of semicircular canal afferent in the same way as

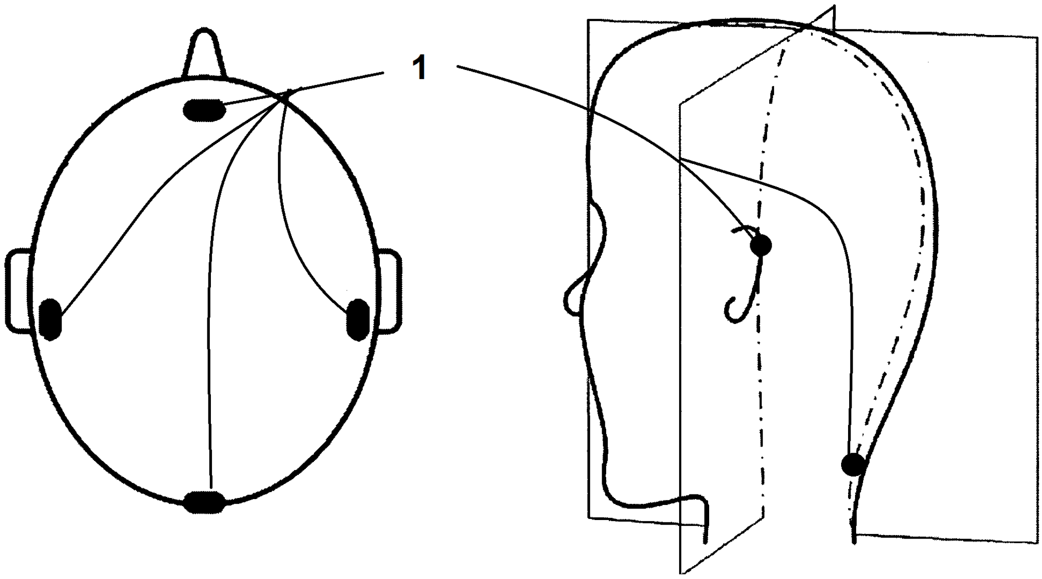

Figure 2-8.: Electrode placement of the galvanic vestibular system (1 electrodes) (Cevette and Galea, 2014)

angular acceleration, and GVS responses are the same for afferent from the otholith organs and the semicircular canals.

Various research has been made into the use of galvanic vestibular stimulation in terms of simulators, directional cueing, and alleviating symptoms of motion sickness. However, current technology still needs many improvements. GVS technology has been applied to users causing them to physically move from side to side. However, there is a need to develop this technology to be more precise and accurate as well as to be able to move a person in many different directions, including forwards and backwards (Cevette and Galea, 2014).

2.3 Motorcycle simulators throughout history

Nowadays as an engineer it is common to have heard about driving simulators or even to have tried one. To get a more extensive knowledge about motorcycle simulators, this section shows a simulator's classification and a journey through history, describing different motorcycle simulators.

Considering the different features of simulators, several assortments can be made. Figure 2-9 shows some of these classifications.

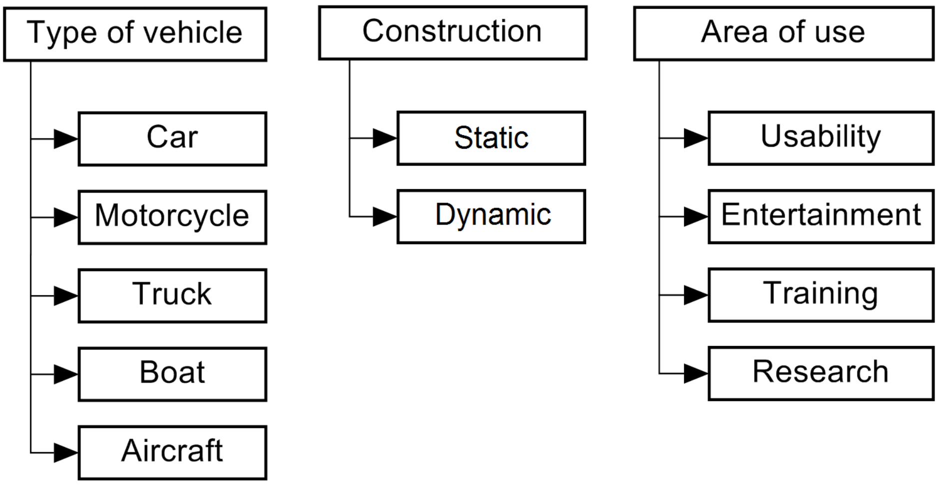

Figure 2-9.: Classification of driving simulators

In view of the type of vehicle, there are simulators for cars, motorcycles, trucks, boats and aircrafts among others. To continue with this assortment it is necessary to know the difference between static, where the mock-up does not move, and dynamic simulators, where the mock-up moves and can represent accelerations. Finally and in the light of the area of use, it is possible to make a difference between usability, entertainment, training and research simulators (Slob, 2008).

Throughout history different motorcycle simulators have been developed and the following paragraphs explain in this regard the most interesting examples with their relevant characteristics.

Training simulator design by Dahl in 1972

In 1972 a motorcycle riding simulator was built and presented by Christian W. Dahl. Figure 2-10 shows a training simulator to provide future motorcycle riders with experience in the starting, stopping, steering, braking, gear shifting in a safe stationary environment prior to actually riding the motorcycle.

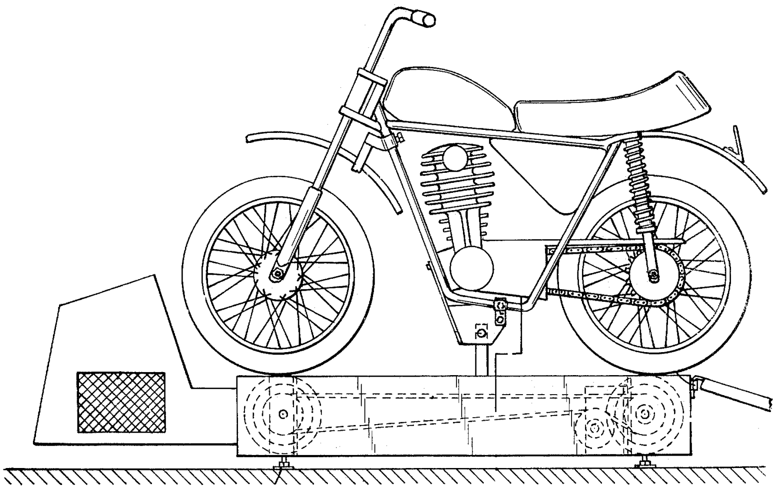

Figure 2-10.: Training simulator design by Dahl in 1972 (Dahl, 1972)

A supporting structure in which the motorcycle was mounted on took care of the motion and provided a simple and effective support, balance and motion. One of the advantages of this simulator with no display resided on the simplicity of the construction and adjustment, making it readily portable and adaptable for indoor or outdoor use (Dahl, 1972).

Research simulator design by Born in 1989

One of the first research motorcycle simulators was developed by Dr. Karl-Peter Born from 1984 to 1989 during his PhD. It was a dynamic research simulator for traffic safety and was used to obtain information about the motorcyclist such as the behaviour of novice riders or those who drive under the influence of alcohol.

The simulator tried to reproduce all the characteristics of motorcycles and was based on a BMW K100 as central element. In this simulator a device could be found on the

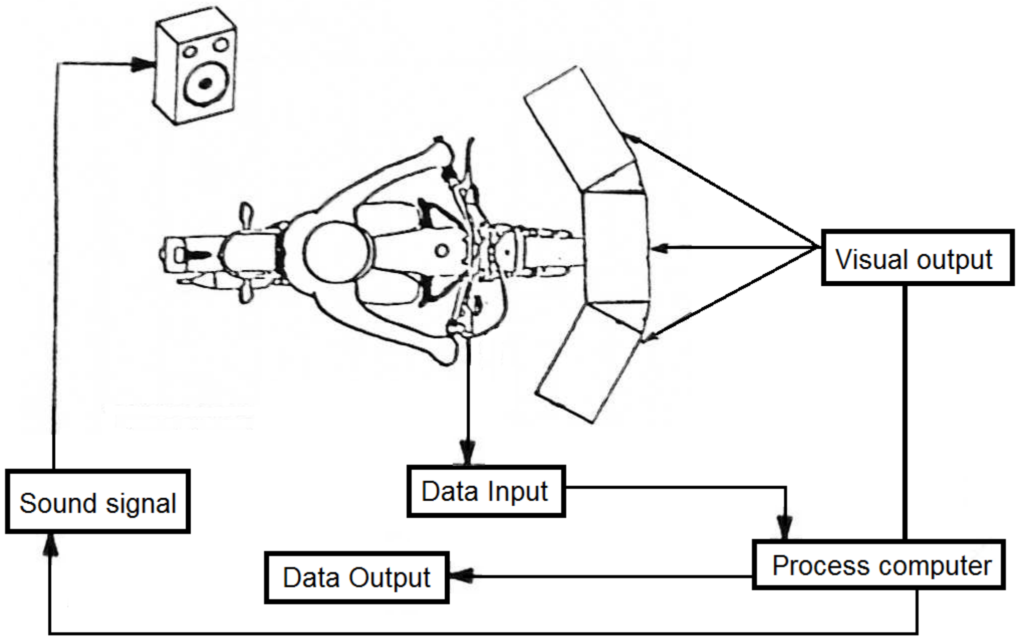

Figure 2-11.: Research simulator design by Born in 1989 (Born, 1989)

upper body of the subject commanded by a compressed air cylinder to simulate long-term accelerations. This belt could be considered the origin of the G-Vest developed in this thesis (Born, 1989).

Training simulators developed by Honda

In 1988 Honda began to develop a series of motorcycle simulators with the aim of training driving skills and experiencing hazardous situations of new riders. The first prototype shown in figure 2-12 was assembled in 1989. However, the results were not as expected and people were unable to ride. The simulator did not represent any acceleration and the riders could not feel the posture of the motorcycle body. After that the aim of the simulator was changed so anybody could easily ride and have the feeling of riding on motorcycles.

This first prototype had several problems (Chiyoda and Sugimoto, 2002):

- In extremely slow speeds, the riders could not ride on the simulator
- In the cornering situation, the riders could not drive along the corner. This was because the centrifugal force was slightly different from that of the real motorcycle

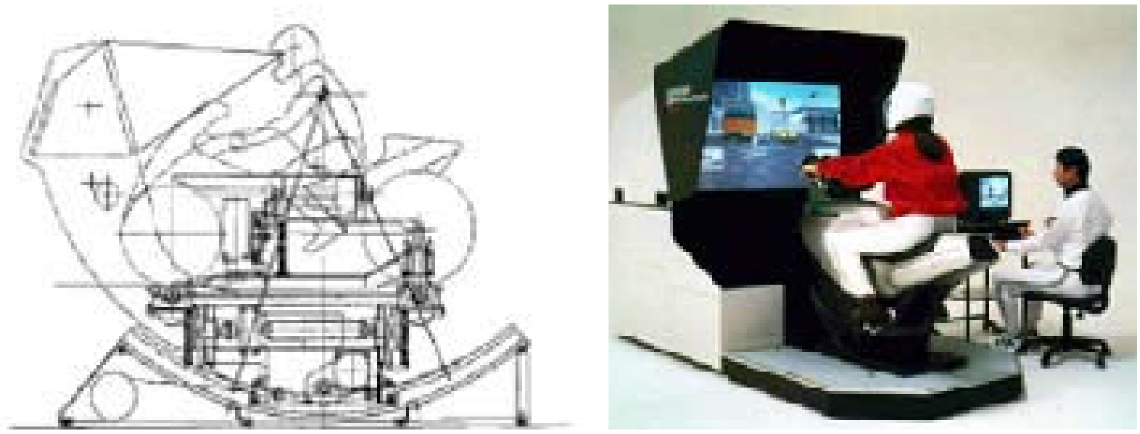

Figure 2-12.: Left part: First prototype of the training simulator (Yamasaki and Miyamaru, 1996). Right part: Third prototype of the simulator (Honda, 2015)

- In the entrance of a corner, the riders had a tendency to steer first towards the same direction of the corner. The inverse steerage did not appear in the simulator.

In 1990 it came the second prototype with the objective of improving the educational functions and making the device compact in size. This simulator was considered one of the first riding simulators for educational purpose and in two years it was used by a total of 3500 riders. Finally it was developed a third prototype shown in figure 2-12. This one was developed making efforts for the reduction of costs and thinking towards a mass production (Yamasaki and Miyamaru, 1996).

Research simulator for designers

In 1995 the simulator shown in figure 2-13 was developed and it was conceived as a tool for the designer to acquire data on motorcycle handling and stability at the design stages as well as to collect data about the rider's control behaviour. The principal objectives of this simulator were (Ferrazzin et al., 2001):

- To become a tool in the motorcycle development phase: speed up this phase and reduce the building of prototypes (time and money)
- To become a market research tool in order to evaluate the customers' satisfaction
- To simulate riding conditions and analyse the information of these simulations without undergoing the risks associated with the specified riding conditions

Figure 2-13.: Left part: Mock-up subsystem. Right part: Integrated simulator (Ferrazzin et al., 2001)

The simulator consisted on a mock-up of a scooter (shown in the left part of figure 2-13) with all the standard functions integrated and mounted in a motion base that provides accelerations. In addition, there was a real time subsystem which acquired the absolute position of the rider's head inside the Virtual environment and evaluated the point of view of the rider (Ferrazzin et al., 2001).

Motorcycle simulator from University of Padua developed by Vittore Cossalter

The University of Padua under the direction of Prof. Vittore Cossalter designed and built a motorcycle mock-up simulator over a period of seven years. It was developed to test devices such as ABS, traction control and other ARAS in a controlled, safe environment and to study riders' behaviour as well as to train them. With this work, it was possible to reproduce and consequently analyse the most critical and risky situations that a normal rider could find frequently on all kinds of roads.

A small group of highly skilled riders helped to fine-tuning of the motion, sound and visual rendering devices. Moreover, it was made a validation by doing a comparison between

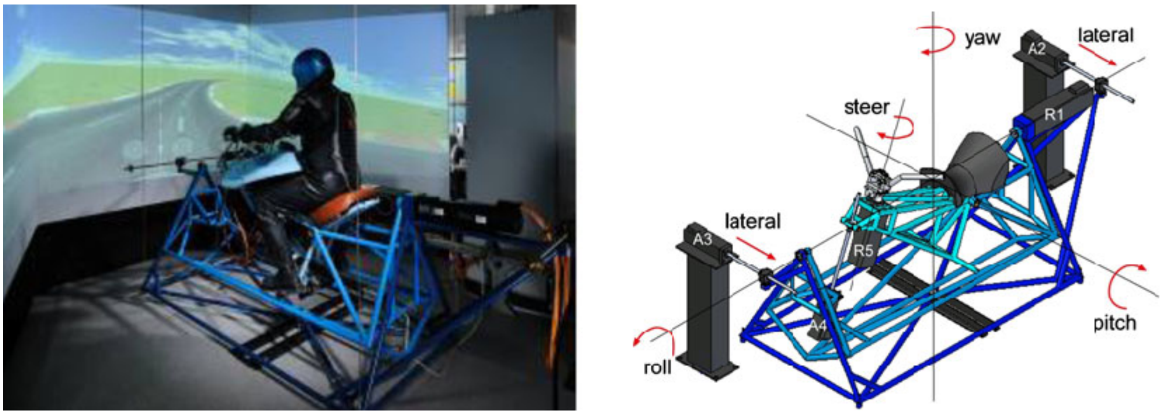

Figure 2-14.: Left part: Integrated simulator. Right part: Sketch of the mock-up structure (Cossalter and Stefano, 2010)

the behaviour of the real and virtual motorcycle during the same riding actions. The validation was conducted on a group of twenty subjects and demonstrated that the simulator reproduced with a good approximation the physics of a real motorcycle (Cossalter and Stefano, 2010).

3 Concept

The aim of this project is the construction and validation of a system to reproduce long-term accelerations for motorcycle simulators. This chapter explains why there is a need to find a new system for them. In order to understand this need, it is explained why the problem is not solved by simply placing a motorcycle on a car simulator, even though these simulators have been more studied and developed for a longer time than motorcycle ones. Secondly, it explains the reason why the actual systems in use to represent accelerations (see section 2.2) are not a good option to be adapted. The third point of this chapter talks about the forces occurring when riding a motorcycle and the reactions it arouses on the rider, which are the reactions that the system has to represent. Finally, there is presented the idea of a system, named G-Vest, illustrating the effect mechanism and also why it causes similar reactions on riders to those during a real ride.

3.1 Assessment of placing a motorcycle on a car simulator

The section below explains the representative profiles of velocity and accelerations of cars and motorcycles. This knowledge is the basis to decide whether an integration of a motorcycle in a car simulator is impossible or not.

One significant difference between car and motorcycle is based on power and weight. As an example, it is made a comparison between the motorcycle BMW K 1600 GT, used as mock-up for the simulator this work covers, with a BMW 320d touring car which serves as mock-up in the dynamic driving simulator from BMW-Forschung und Technik. With a higher weight-to-power rate of a motorcycle compared to a car, its maximal acceleration is much higher. For instance, the BMW K 1600 GT takes 3.2 s to accelerate from 0 to 100 km/h whereas the car needs 7.7 s. The motorcycle reaches an acceleration of

8.7 m/s^2 and the car 4.1 m/s^2. Acceleration is an important fact because it defines which kind of system can be used to reproduce accelerations for the designed simulator. Table 3-1 sums up these values.

Value	BMW K 1600 GT	BMW 320d touring
Acceleration 0-100 km/h	3.2 s	7.5 s
Max. acceleration	8.7 m/s^2	4.1 m/s^2
Wet weight	348 kg	1580 kg
Power	160.5 hp	184 hp

Table 3-1.: Comparison between BMW K 1600 GT and BMW 320d touring

After the review of the values of acceleration in real vehicles there is a short review of the values of simulated accelerations on a car simulator. The use of tilt-coordination to simulate long-term accelerations is widely used on car simulators. Figure 3-1 shows the accelerations that can be represent with an hexapod.

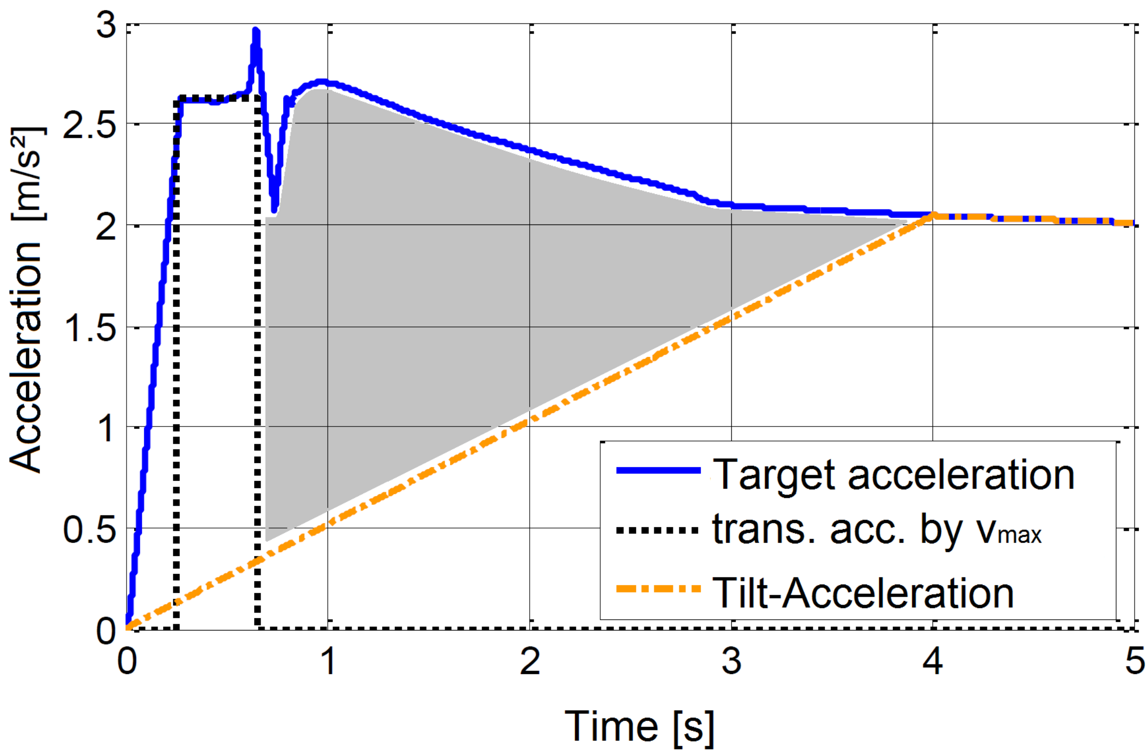

Figure 3-1.: Representation of accelerations with an hexapod (Guth, 2013)

The blue line indicates the target acceleration and the orange line the acceleration represented using tilt-coordination. It can be observed that the target acceleration is above the simulated acceleration and there is a big zone (grey) that cannot be represented. Despite the fact of the widely use on car simulators, it is clear that an acceleration zone cannot be represented with this system. Considering the bigger values of acceleration of motorcycles (explained in the first part of the section), this grey area would be bigger and the results would not be close to reality. That is the reason why the conversion of a car simulator into a motorcycle simulator is not recommendable.

3.2 Assessment of current systems to reproduce accelerations

After seeing the impossible adaptation of a car simulator, this section explains the possible integration of systems from section 2.2 to simulate long-term accelerations.

First of all, the hexapod can be used in two different configurations: with a fixed projection independent from the platform or in a tilt-coordination configuration. The use of the first configuration is widespread in motorcycle simulators. Nonetheless, the accelerations that can be represented belong to the category of short-term accelerations (see introduction).

To have an order of magnitude, it is possible to think of a hexapod like the W10 from the company Ckas (Ckas, 2015) with a displacement of ± 150 mm and an acceleration of ± 5 m/s^2. Taking into account the acceleration and deceleration of the hexapod, it permits to simulate the maximal acceleration during approximately 0.2 s. If we think of a platform with the same values, but double in size, this time is 0.3 s. It only represents 1.42 times longer. As figure 3-2 shows, that is because time is not directly proportional to acceleration but its square root.

In the second configuration the participant does not have any external reference and it is used the tilt-coordination method. As explained in the previous section (see figure 3-1) there is a big range of acceleration that cannot be represented with tilt-coordination, because of the maximal rotation speed (3°/s) and the maximal angle before the person realizes about the inclination (20-30°).

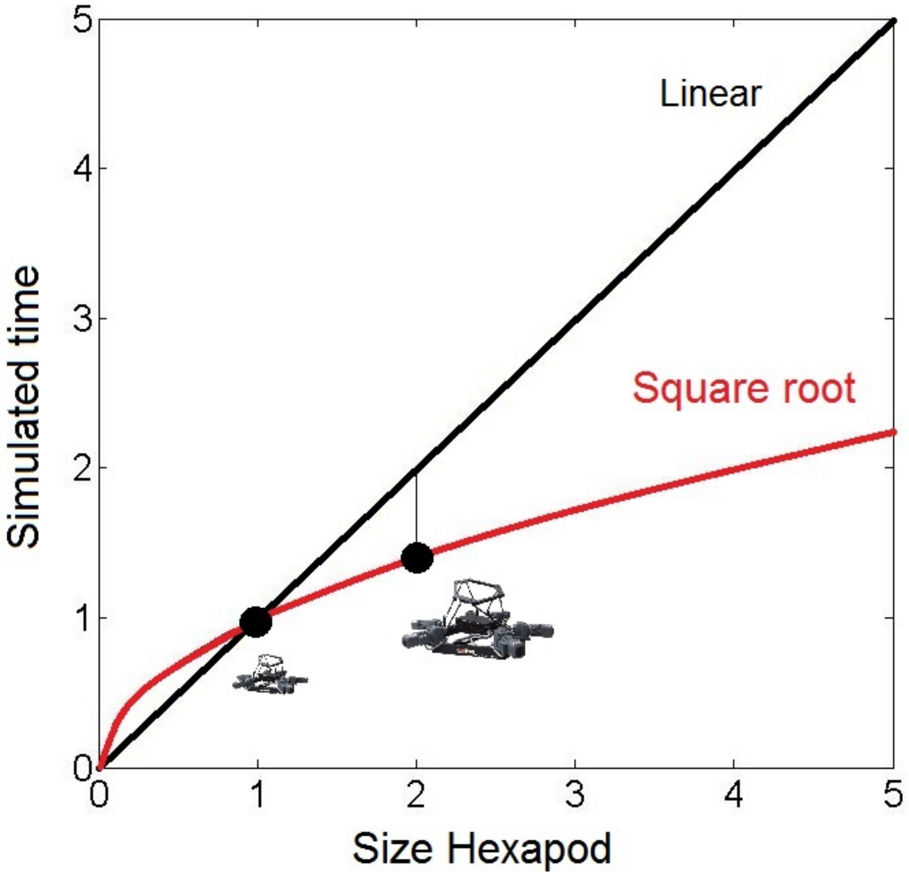

Figure 3-2.: Increase of the simulated acceleration depending on the increase of size of the hexapod

As for the G-Seat, widely used in aircraft simulators providing *stimuli* for long-term accelerations (Kron, 1975),it cannot be used for motorcycle simulators because of the different shape of a motorcycle's seat.

The Galvanic Vestibular system can easily be adapted, allowing a complete mobility on the motorcycle simulator. In fact, it only needs an adaptation to integrate the electrostimulators in order to allow the participant to wear a helmet. Nevertheless, this system presents two fundamental problems: the first one refers to the phase of development of the system, since it does not permit a good control for the simulation. The second one refers to the possible non-acceptance from the participants, due to fear of the electrostimulations and the use of electric shocks.

Table 3-2 sums up the positive and negative characteristics of the named systems. As it can be noticed, the lack of an existing system that could be adapted to the motorcycle

System	Participants' acceptance	Simulation of long-term accelerations	Integration on a motorcycle simulator
Hexapod	+++	—-	+++
G-Seat	+++	+++	—-
GVS	—-	—-	+++

Table 3-2.: Comparison between current systems to reproduce accelerations

simulator promotes the construction of a new one which covers the specific necessities of the simulator.

3.3 Inertial and airflow-induced forces on a rider

The previous section has shown the lack of a system to represent long-term accelerations. This section goes through the forces (inertial and airflow-induced forces) that the creation to reproduce long-term accelerations has to represent. Moreover, it shows how real bikers perceive these forces.

When accelerating a motorcycle ($a_{motorcycle}$) an acceleration appears on the rider (a_{rider}) that has a certain mass m_{rider}. It is considered that the rider does not move during the acceleration and therefore both accelerations are the same ($a_{rider} = a_{motorcycle}$). The equation 3.1 presents the force on the rider:

$$\overrightarrow{F_{rider}} = m_{rider} \cdot \overrightarrow{a_{rider}} \tag{3.1}$$

The force is shared in proportion to the mass of the different parts of the body. As equation 3.2 demonstrates, the force on the upper part of the body $F_{Upper\ Body}$ corresponds to the force on the rider multiplied by a mass factor ($k_{Upper\ Body}$). The mass factor of different parts of the body can be seen at table 3-3.

$$\overrightarrow{F_{UpperBody}} = \overrightarrow{F_{rider}} \cdot k_{UpperBody} \tag{3.2}$$

Body Part	Relative weight[%]
Head	7,06
Trunk	42,70
Upper arm	3,36
Forearm	2,28
Hand	0,84
Thigh	11,58
Lower leg	5,27
Foot	1,79

Table 3-3.: k-Relative weight distribution of the human body (Söll, 1982)

However, as Newton says in the first law of physics, an object at rest stays at rest and an object in motion stays in motion with the same speed and in the same direction unless acted upon by an unbalanced force. That is why the rider feels a force, known as fictitious force, that throws him right backwards when accelerating. Figure 3-3 shows this fictitious force that actuates upon the rider when accelerating the motorcycle. That force activates the mechanoreception and proprioception canals of the rider and causes the strain of the muscles on the arms, trunk and legs, as well as a strong grip of handlebars in order not to fall of the motorcycle.

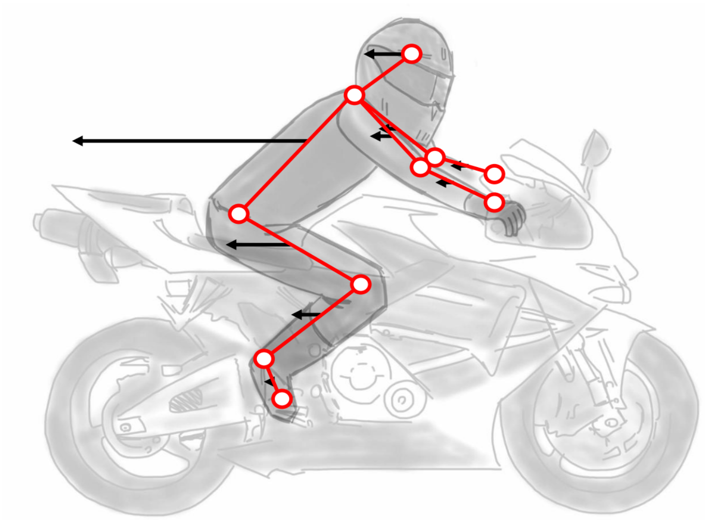

Figure 3-3.: Fictitious force on the rider when accelerating the motorcycle (Hanselka, 2014)

In addition to the more theoretical aspects involved in the design and conception of the simulation of acceleration, it is also important to take the opinion of the riders into consideration, in order to create a realistic cue, which is not only based on technical data but on experiences too. To do so, the results from a survey have been taken and analysed (Hanselka, 2014). The following questions asked to motorcyclists help to provide an idea of the most common reactions that occur when riding, due to inertial and airflow-induced forces.

The first question of the survey examines the reaction of the rider during acceleration:

"During the acceleration of a motorcycle high inertial forces actuate on the rider, which push him/her backwards. In order not to fall of the bike during acceleration process it is necessary to support this inertial forces. What is your strategy to support these forces?"

The possible answers are:

a) I hold the handlebars firmly in order not to fall back.

b) I tension legs, back, and abdominal muscles in order not to fall back.

c) I combine both possibilities.

d) Another answer.

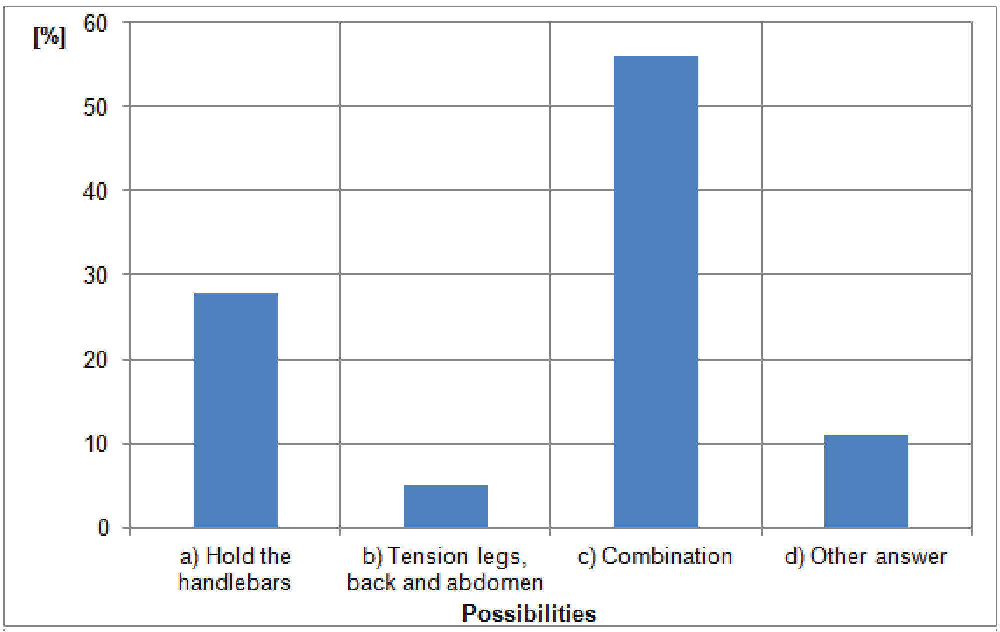

Figure 3-4.: Questionnaire result for the acceleration behaviour

As seen in the results (see figure 3-4 (Hanselka, 2014)), more than a half of the respondents do a combination of possibilities a) and b), meaning that they use the hole body to counteract the force of acceleration. The new simulation system should provoke this response in order to represent long-term accelerations in a realistic manner.

Similarly when braking, a force to the backwards appears, although since the fictitious force is acting forwards the rider feels that something pushes him towards the front, so his reaction is to stiffen his body to prevent his head from crashing into the tachometer. In this case, riders can lean theirs knees to the tank and avoid this movement. This force is represented in figure 3-5, where the forces acting on each part of the rider's body can be seen.

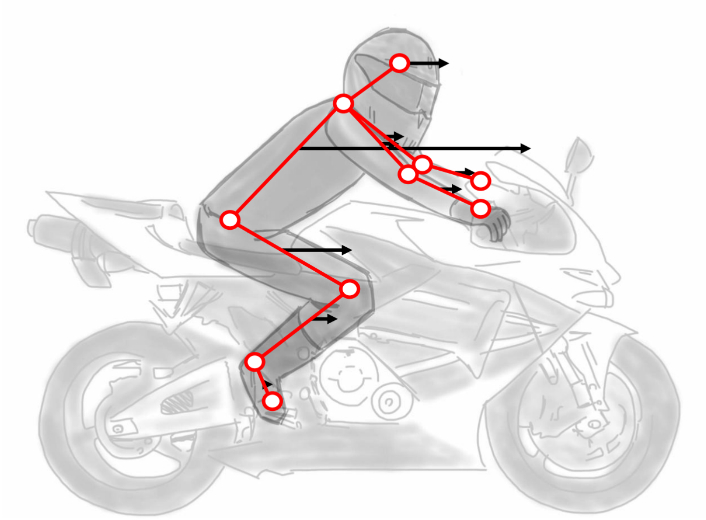

Figure 3-5.: Fictitious force on the rider when braking the motorcycle (Hanselka, 2014)

The next question of the survey relates to the braking response of the rider, whose results can be seen in figure 3-6 (Hanselka, 2014):

"When braking the motorcycle, the riders' body is pushed forwards due to forces of inertia. In order not to fall of the bike during braking process it is necessary to support this inertial forces. What is your strategy to support these forces?"

The possible answers are:

a) I stiffen my torso with my arms on the handlebars.

b) I tension my legs, back, and abdominal muscles in order not to fall forwards.

c) I combine both possibilities.

d) Another answer.

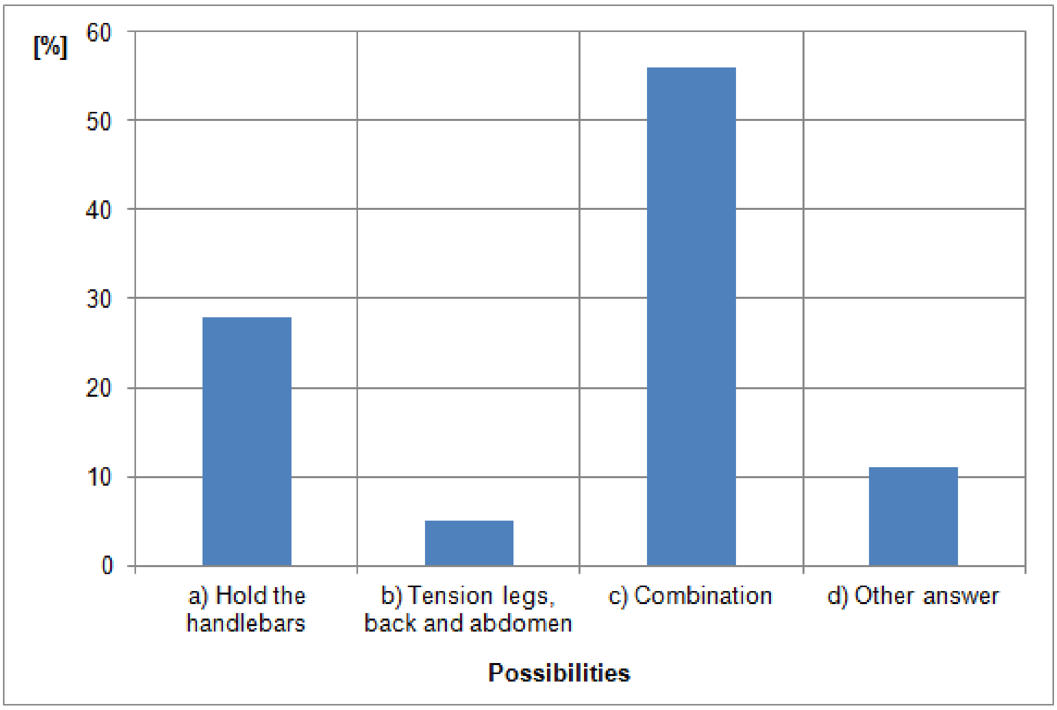

Figure 3-6.: Questionnaire result for the braking behaviour

The results obtained from this question are similar to the acceleration's ones, as about a half of the respondents employ the whole body in their reaction. That means that the same system can be used to simulate both the acceleration and braking situations.

Furthermore, when riding a motorcycle it appears a force on the rider induced by the airflow (see equation 3.3). This force depends on a wind coefficient (c_w), the expose area of the rider to the air (A_{rider}), the density of the air (ρ_L = 1,293 [kg/m^3] for 0 °C and 1,013 bar) and the square of the relative flow velocity between the rider and the air.

$$F_{w,L} = c_w \cdot A_{rider} \cdot \frac{\rho_L}{2} \cdot {v_{rel}}^2 \tag{3.3}$$

As said, the airflow-induced force is proportional to the square of velocity and for this reason, this force is negligible at low speed but can be very important at high velocities. Attending to the type of motorcycle, the impact of the airflow on the rider is very variable. It varies from touring and sport motorcycles where the airflow induced force is negligible because of the motorcycle fairing up to the naked bike where the rider has to beat this force in order not to fall of the bike. The following figure 3-7 shows the effects of the airflow on a motorcycle with partial fairing.

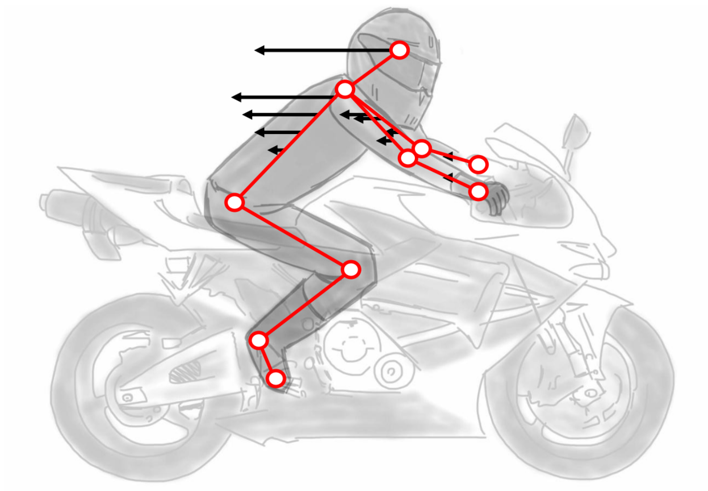

Figure 3-7.: Airflow-induced forces on the rider when riding the motorcycle (Hanselka, 2014)

In this case, the opinion of riders is also important to integrate both forces in the same system. The following question, which results are in figure 3-8, helps to understand how airflow affects the motorcycle's rider (Hanselka, 2014):

"Thinking of a steady ride at higher speeds and depending on the type and design of the motorcycle and the type of clothing of the rider against the airflow-induced forces: where do you perceive the airflow-induced forces?"

The possible answers are:

a) I perceive the airflow-induced foreces by a pressure on the head/helmet.

b) I perceive the airflow-induced foreces by a pressure on the upper part of the body.

c) I perceive the airflow-induced foreces by this "flutter" to my clothes.

d) Other answer.

In this case the respondents are allowed to choose all the answers that could correspond, so more than one answer is possible.

The results show that the airflow-induced forces mostly affects the upper part of the body and the head, where the airflow protection is fewer.

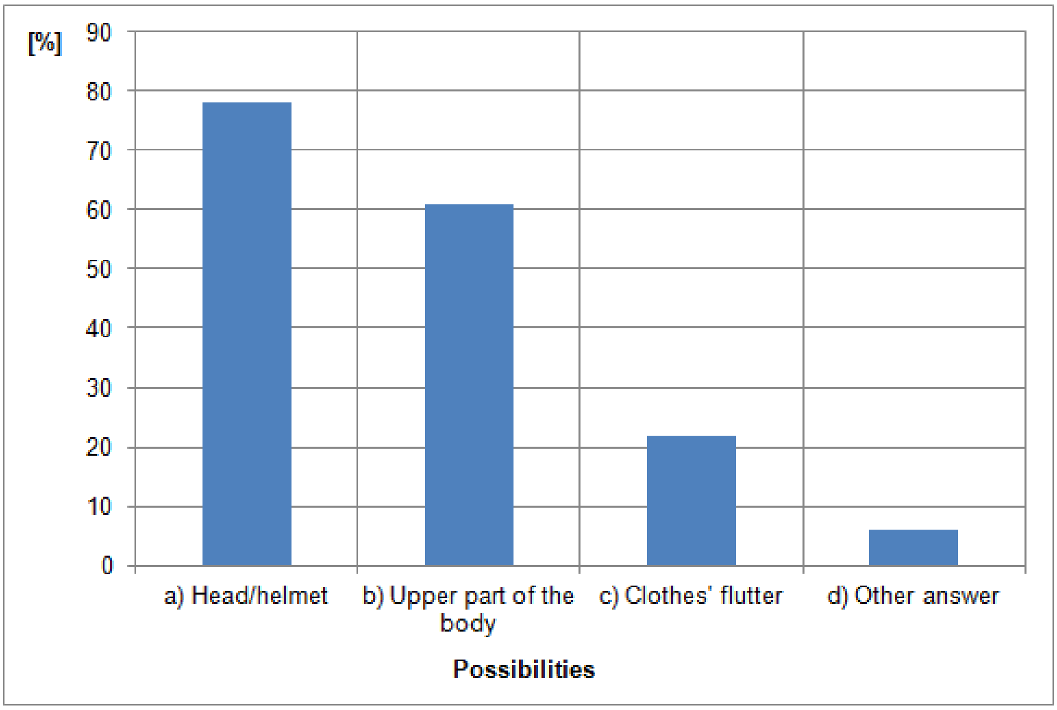

Figure 3-8.: Questionnaire result for the perception of the airflow-induced force (Hanselka, 2014)

3.4 Presentation of a concept to reproduce long-term accelerations on a motorcycle simulator

After a review of the forces on a biker and an analysis of the most common reactions, it is now possible to explain the idea of the system described below. It must be faced the difficulty of representing an acceleration without producing one. The obstacle is not only the representation of acceleration and airflow-induced forces, but also the fact that the rider can recognize these forces as an acceleration.

As read in section 2.1.4 perception of acceleration in the body results from the integration of information coming from the somatosensory, visual and vestibular systems. Section 2.2 explains the systems to simulate long-term accelerations. There are two systems (the "Galvanic Vestibular System" and the "G-Seat") that only use one channel to represent accelerations. The first one stimulates the vestibular organs without stimulating the proprioception channels giving a more realistic view of driving and accelerating vehicle such as a boat, airplane, automobile and motorcycle (Cevette and Galea, 2014). In this case the balance system interprets the signals from the Galvanic Vestibular System as a real head movement in space (Fitypatrick and Brian, 2004). The second one is the "G-Seat", which stimulates the somatosensory system giving a motion sensation similar to the one experienced during the actual operation of a vehicle (Cardullo and Kron, 1976).

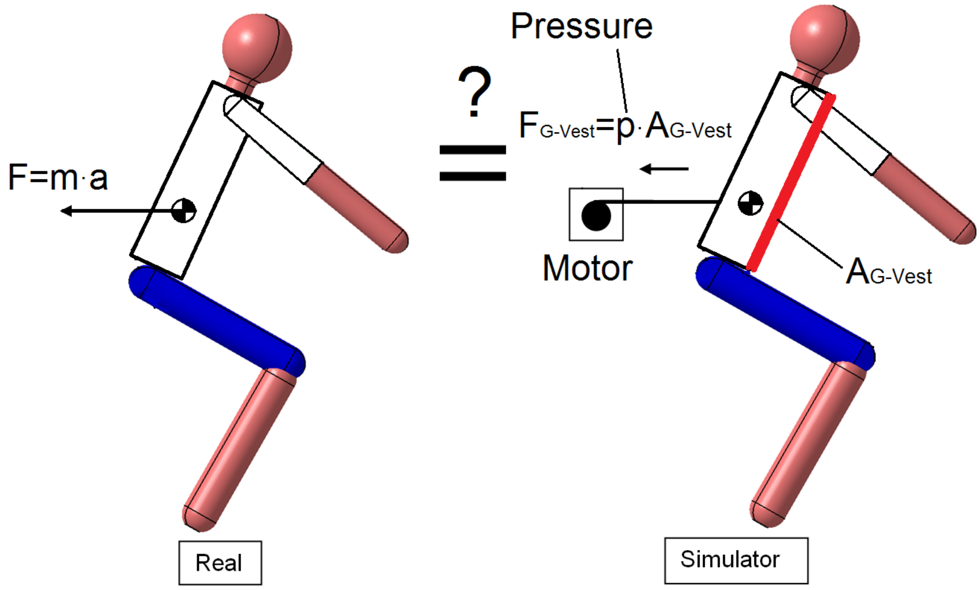

Figure 3-9.: Representation of the volume force (left) and the pressure (right). The G-Vest generates this strength to simulate the real volume force

Taking the G-Seat as a model to provide long-term accelerations, the concept of the system, named G-Vest, is based on the representation of the inertial and airflow-induced forces on a motorcycle simulator without moving the biker. The G-Vest stimulates the somatosensory system (mechano- and proprioception) through a pressure on the torso of the biker.

The concept of the system has some simplifications between the reality and the simulation. Firstly it simulates a volume force (inertial one) through a pressure on the torso (see figure 3-9). It is important that the pressure ($P_{G\text{-}Vest}$) is distributed over the contact surface ($A_{G\text{-}Vest}$) between the vest and the participant so that rider does not realize about the pressure and interprets it as the inertial force. The second simplification is the concentration of the airflow-induced force on the torso, without stimulating the head. Finally, the G-Vest simulates accelerations (due to inertial force) without stimulating the vestibular system.

4 Construction

The chapter explains the previous systems than can be considered the predecessors of the G-Vest. Subsequently it comments the simplifications achieved and the value of the forces that are going to be represented by the G-Vest. The chapter continues with a review of the components of the construction and their integration in the simulator. To finish, there is a brief overview of the control system.

4.1 Background

Looking throughout history, some predecessors can be found in relation to the construction of a system with the same objectives as the G-Vest.

The first construction appears in the work of Born (Born, 1989). It was built with an air cylinder, which was anchored to the wall and the actuator was linked by a belt construction to the upper part of the body.

The second construction was carried out by the TU Darmstadt and it focused on the union between the system and the participant. The system was composed of a backpack and a climbing harness connected together with some ribbons, as seen in figure 4-1. In this case there is no actuator and a second person develops the force needed during the simulation (Hanselka, 2014).

Figure 4-1.: Left part: System consisting of a backpack and a climbing harness. It is set of the braking configuration. Right part: The system during the simulation. (Hanselka, 2014)

The third construction was also carried out by TU Darmstadt and this time the whole system was developed but only in a minimalistic version. The creation, as seen in figure 4-2, is integrated into the motorcycle through its assembly on an aluminium profile. It is composed of an electric motor joined with a pulley, where the rope is collected. The rope transmits the force to the vest, which is composed of a shoulder vest construction filled with air cushion foil. The iron bar with a form of a semicircle (see figure 4-2) allows that the length between the bar and the motor remains constant (Anton, 2015).

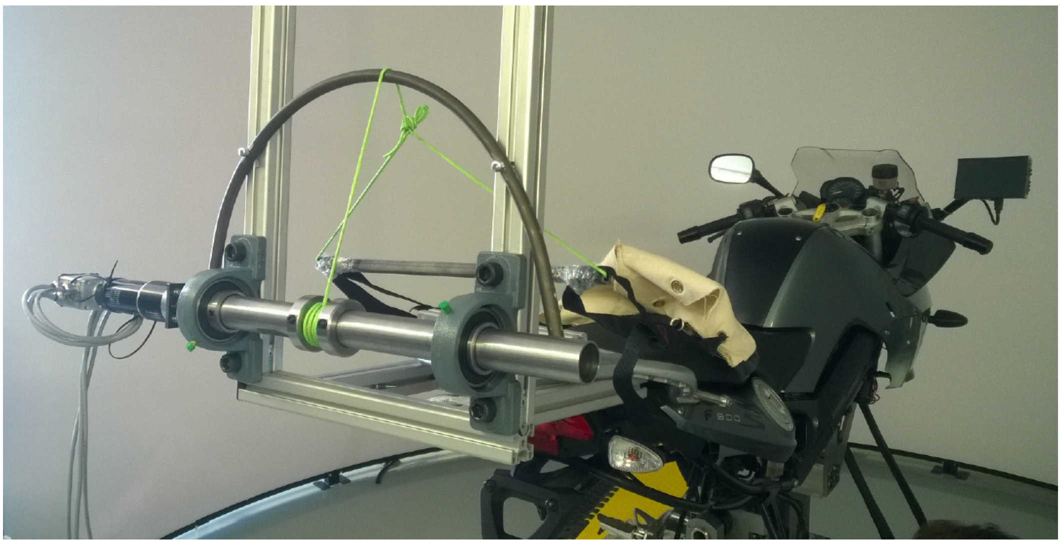

Figure 4-2.: Integration of the system in the WIVW simulator (Anton, 2015)

4.2 Requirements

This section clarifies the forces that the G-Vest represents, as well as their values.

The invention simulates both the inertial and airflow-induced forces. Firstly, the inertial forces, as said in section 3.3, depend on the mass of the person and also on the acceleration. As reference is taking a person of 72 kg (m_{rider}), a k, that represents the mass associated to the upper body of 56 % and a maximal acceleration of 8.7 m/s^2 (see chapter 3). The inertial force ($F_{inertial}$) is calculated using the equation 4.1.

$$\overrightarrow{F_{inertial}} = m_{rider} \cdot k \cdot a_{rider} = 351N \tag{4.1}$$

The second force to be simulated corresponds to the airflow-induced forces, where main the part affects to the upper section of the body. The area of the rider (A_{rider}) exposed is around 0.14 m^2 and the biker has a wind coefficient of 0.47 (Hucho, 2015). Moreover, the velocity is limited to 200 km/h.

$$\overrightarrow{F_{airflow}} = c_w \cdot A_{rider} \cdot \frac{\rho_L}{2} \cdot {v_{rel}}^2 = 131N \tag{4.2}$$

Overall the system should be able to simulate a maximal force of 482 N (see 4.3).

$$\overrightarrow{F_{G-Vest}} = \overrightarrow{F_{inertial}} + \overrightarrow{F_{airflow}} = 482N \tag{4.3}$$

4.3 Components and construction

The general configuration on the G-Vest is shown on 4-3. The prototype is integrated in the simulator, with a reduced weight and an easy assembly that would permit its integration into other simulators.

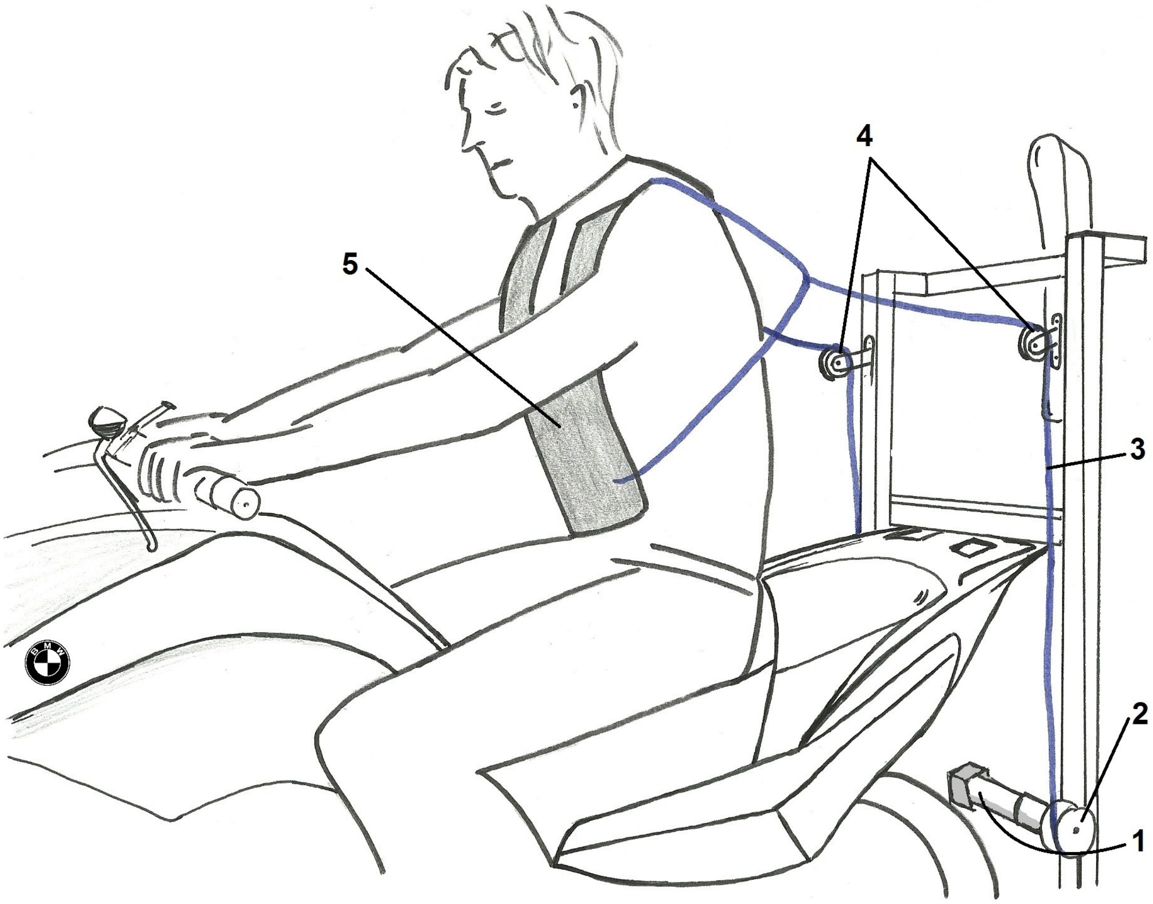

Figure 4-3.: Sketch of the G-Vest (1 Motors, 2 pulleys, 3 rope, 4 free pulleys and 5 vest)

The system consists on a Vest (5), two free pulleys (4), a rope (3), two pulleys (2) and the motors (1).

The vest (5) applies the pressure on the torso of the biker and avoids punctual forces on the rider to maximize the comfort. The rope (3) links the vest with the motors. The free pulleys (4) guide the rope and allow the movement of the rider over the motorcycle. The rope winds up in the pulley (2), one for each motor. The pulley is custom-made built to fit perfectly in the axe of the motor to which it is fixed by a screw. It has a radius of 25 mm and three different holes that permit the utilisation of ropes from distinct diameters.

An important part of the G-Vest is the two motors (1). One of them is shown in figure 4-4. It corresponds to an electronically commutated electric motor joined with a planetary gearbox. Characteristics of both can be found in the table 4-1.

Figure 4-4.: Electri motor with planetary gearbox

Electric motor	
Nominal speed	10000 min^{-1}
Nominal torque	316 mNm
Nominal current	7.94 A
Torque constant	42.7 mNm/A
Speed constant	224 min^{-1}/V
Gearbox	
Speed reduction	12:1
Max. radial load	420N
Max. initial speed	6000 min^{-1}

Table 4-1.: Characteristics of motor and gearbox

Moreover, the simulator is provided with two ventilators to represent air and ameliorate the airflow sensation.

The G-Vest is integrated with an aluminium profile, allowing the facility to change the measurements and its replacement in the future through customised pieces. Both motors and their controls are located at the lower part of the motorcycle out of sight for the rider, avoiding the fact that he becomes distracted with non motorcycle components.

4.4 Control

This part explains the control system used for the G-Vest. Figure 4-5 shows the structure of the signal path. As said in section 4.2 the force of the system depends on the acceleration and velocity of the motorcycle. The control of this is integrated in the program that drives all the elements during the simulation.

Using the Simulink tool in MATLAB, the signal is treated through different blocks to calculate and to adapt the signal to the electric motors of the system. First of all, velocity and acceleration are filter to produce a smooth signal. This is then calculated with the parameters already named and a conversion parameter is used to convert the forces to the necessary current for each motor.

This output is sent by CAN Bus to the power electronics that creates a PWM signal, suitable for the motors.

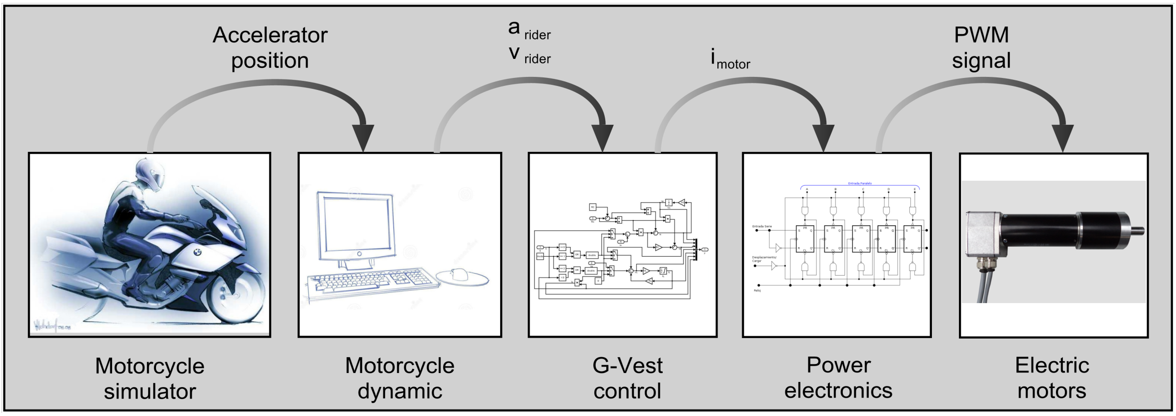

Figure 4-5.: Structure of the signal path

5 Research Study

This chapter explains the research study conducted through this work and it responds to the central question:

"Can the G-Vest be used to simulate long-term accelerations on a motorcycle simulator?"

The first part of this chapter explains the hypotheses which are answered with this study. This section is followed by the explanation of the method, where the information about the participants, the simulator, the experimental conditions and the experimental protocol is clarified. Then there are the results of the study and the chapter ends with a discussion of this conclusions and the acceptance or rejection of the hypotheses.

5.1 Research hypothesis

After the integration of the G-Vest on the motorcycle simulator, a research study is carried out to proof the functionality of the system. This study investigates the differences between driving the simulator with and without the G-Vest regarding the impression of realism. This study helps to approve or refuse the effectiveness of this type of system and sets a base for future developments in motorcycle simulators. Table 5-1 shows the hypotheses of the study.

Nº	**Hypothesis**		**Indicator**
1	H_0	The inertial force during riding a motorcycle cannot be represented by a surface force on the torso	Subjective question
	H_1	The inertial force during riding a motorcycle can be represented by a surface force on the torso	
2	H_0	The airflow-induced forces cannot be represented by surface forces on the torso	Subjective question
	H_1	The airflow-induced forces can be represented by surface forces on the torso	
3	H_0	The perception of acceleration riding a motorcycle is unrealistic without exciting the vestibular system	Subjective question
	H_1	The perception of acceleration riding a motorcycle is realistic without exciting the vestibular system	
4	H_0	The freedom of movements whit the G-Vest is guaranteed	Objective data
	H_1	The freedom of movements with the G-Vest is not guaranteed	
5	H_0	The G-Vest is uncomfortable	Subjective question
	H_1	The G-Vest is comfortable	

Table 5-1.: Study's hypotheses

5.1.1 Assumption one: inertial force

The concept of the G-Vest is based on the simulation of the inertial force through pressure on the torso. The inertial force is a volume force that stimulates the proprioception. However, the G-Vest produces a pressure to stimulate the proprioception and the question that arises is if this pressure is able to represent a volume force (inertial force). There is not any possibility to use any objective data to corroborate this hypothesis. That is why it is a subjective evaluation used through the following question to the participants:

"How realistically do you perceive the inertial force?"

The answer is rated in a scale from "*unrealistic=1*" to "*realistic=9*" with an intermediate value of five. A realistic estimation of the inertial force with the G-Vest signifies that the participants interpret the pressure on the torso as an inertial force (volume force).

∘H_0 : The inertial force during riding a motorcycle cannot be represented by a surface force on the torso.

∘H_1 : The inertial force during riding a motorcycle can be represented by a surface force on the torso.

→ Indicator: Subjective question to the participants

$$H_1 : M_e(\text{question1})_{\text{with G-Vest}} > M_e(\text{question1})_{\text{without G-Vest}}, \quad \text{p-value}<0.05$$

5.1.2 Assumption two: airflow-induced forces

The airflow-induced forces are produced by the relative flow velocity between the rider and the air. The rider, with an exposed area to the airflow that depends on the fairing of the motorcycle, moves a mass of air proportional to this area. This relative velocity induces a pressure on this area (principally the head and the torso) that is detected by the mechanoreceptors. The G-Vest stimulates also the mechanoreceptors through a pressure on the torso to simulate this forces but it not actuates on the head. The question that arises is if the pressure on the torso is enough to represent the airflow-induced forces that actuates also on the head. There is no possibility to use objective data to corroborate this hypothesis. That is why is a subjective evaluation used through the following question to the participants:

"How realistically do you perceive the airflow-induced forces?"

The answer is rated in a scale from "*unrealistic=1*" to "*realistic=9*" with a intermediate value of five. A realistic estimation of the inertial force with the G-Vest signifies that the participants interpret the pressure on the torso as the airflow-induced forces.

$\circ H_0$: The airflow-induced forces cannot be represented by surface forces on the torso.

$\circ H_1$: The airflow-induced forces can be represented by surface forces on the torso.

$\rightarrow$ Indicator: Subjective question of the participants

$$H_1 : M_e(\text{question2})_{\text{with G-Vest}} > M_e(\text{question2})_{\text{without G-Vest}}, \quad \text{p-value<0.05}$$

5.1.3 Assumption three: perception of acceleration

The concept of the G-Vest is based on the simulation of accelerations on a motorcycle simulator using only the somatosensory system. This means that the vestibular one is not stimulated. It arises the question whether the perception of acceleration without exciting the vestibular system is realistic. When it comes to evaluate the question a problem appears. Like it is explained in section 3.2, the hexapod cannot be used to simulate long-term accelerations stimulating the vestibular system and therefore the difference in realism between exciting or not the vestibular system cannot be compared directly. To evaluate this hypothesis it is used the answers of the first question, because the acceleration comes from this inertial force. A realistic answer (greater than five) of the first hypothesis signifies that the perception of acceleration is realistic without the stimulation of the vestibular system. Instead, if the answer of the first question is fewer than five, no conclusion can be drawn. It is impossible with this approach to say, whether the perception of acceleration is unrealistic because of the no excitation of the vestibular system or the unrealistic perception of the inertial force when the realism is rated low.

○H_0 : The perception of acceleration riding a motorcycle is unrealistic without exciting the vestibular system.

○H_1 : The perception of acceleration riding a motorcycle is realistic without exciting the vestibular system.

→ Indicator: Subjective question of hypothesis one

$$H_1 : M_e(\text{inertial})_{\text{with G-Vest}} < M_e(\text{inertia})_{\text{without G-Vest}}, \quad \text{p-value}<0.05$$

5.1.4 Assumption four: freedom of movements

The G-Vest consists of a vest and ropes (see chapter 3.4). Even though the system is designed to give movements freedom to the riders, it can be that the mobility is reduced. To find out if the participants move the same when the G-Vest is activated, the movements of them are measured. For this purpose objective data from the tracking system is used and the maximal values of displacement (forwards, right, left) are compared between the fact of the activation of the G-Vest. The value backwards is not important because the rope of the G-Vest cannot limit the movement along this direction. If the maximum displacement with the G-Vest is equal or greater, it is accepted that the design of the system is correct and it does not restrict the movements of the rider.

$\circ H_0$: The freedom of movements with the G-Vest is guaranteed.

$\circ H_1$: The freedom of movements with the G-Vest is not guaranteed.

$\rightarrow$ Indicator: Maximum displacement forwards, to the right and to the left

$H_1 : M_e(\text{displacement})_{\text{with G-Vest}} < M_e(\text{displacement})_{\text{without G-Vest}}$, p-value<0.05

5.1.5 Assumption five: Wearing comfort

The G-Vest is composed of different elements that the rider have to wear (vest, rope). On the simulator is important that the rider does not distracted by any simulator component in order to have a good immersion during the trial. It can happen that the G-Vest is uncomfortable and get the rider off on the wrong foot getting the immersion worse. Comfort is a subjective impression and it depends on the participants. That is why it is used a subjective evaluation of the participants through the following question:

"Is the G-Vest comfortable?"

The answer is rated in a scale from "*unrealistic=1*" to "*realistic=9*" with a intermediate value of five. It can be said that the G-Vest is comfortable if the answer is greater than five.

This assumption is examined individually and the alternative hypothesis is accepted if the mean value is statistical greater than five. However, it is important to know the opinion of the riders to see how the system can be improved and for that reason there is another question:

"Please explain why the G-Vest is comfortable or uncomfortable."

It is a open questions, where the participants can write his opinions. It is not given any option in order not to show the possible weakness of the G-Vest and condition their answer.

- Assumption five:

  ∘H_0 : The G-Vest is uncomfortable.

  ∘H_1 : The G-Vest is comfortable.

  → Indicator: Subjective question of the participants

$$H_1 : \bar{x}_{withG-Vest} > 5, \quad \text{p-value<0.05}$$

5.2 Methods

5.2.1 Participants

For the study, experienced motorcycle riders from BMW Motorrad are selected. All the participants have a valid driver's license of European A category. The choice of highly experienced participants helps to compare impressions with a real ride on a motorcycle. Altogether, 23 subjects take part in the study but three of them cannot finish it. Two of these cancellations are because of occurring simulator sickness and the other one is due to technical defect.

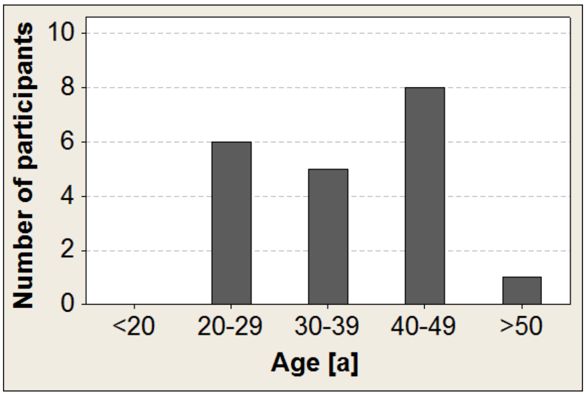

Figure 5-1.: Age distribution of participants

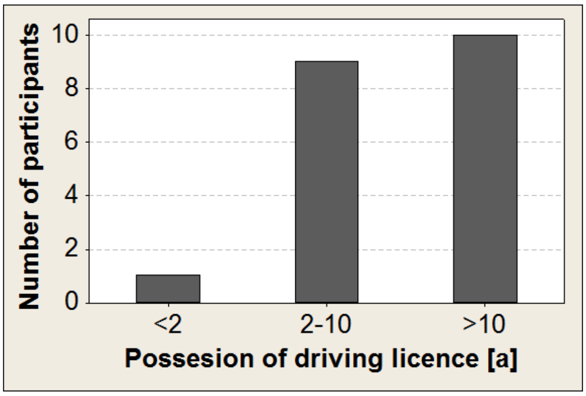

Figure 5-2.: Possesion of driving licence

There are eighteen males and two females with an age range from 22 to 55 years and a mean age of 35.35 years (SD=8.71). The age distribution is shown in figure 5-1. Figure 5-2 shows the histogram of the possession of the driving licence.

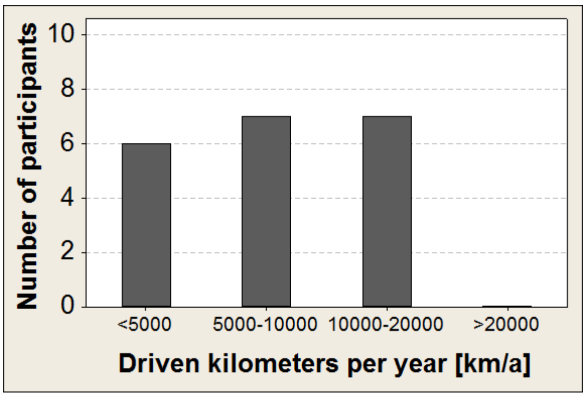

Figure 5-3.: Annual mileage distribution

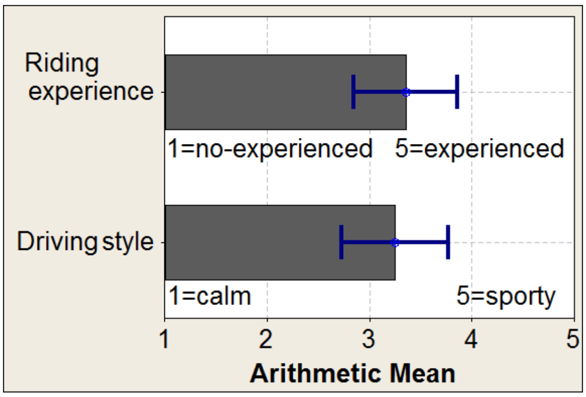

Figure 5-4.: Self-evaluation towards driving

As it can be seen in figure 5-3 six participants drive less than 5000 km annually, seven between 5000 and 10000 km and between 10000 and 20000 km and none of the riders drive more than 20000 km per year. Additionally, self evaluation questions about the experience and the driving style compared to other riders are asked and figure 5-4 shows the results.

5.2.2 Driving simulator

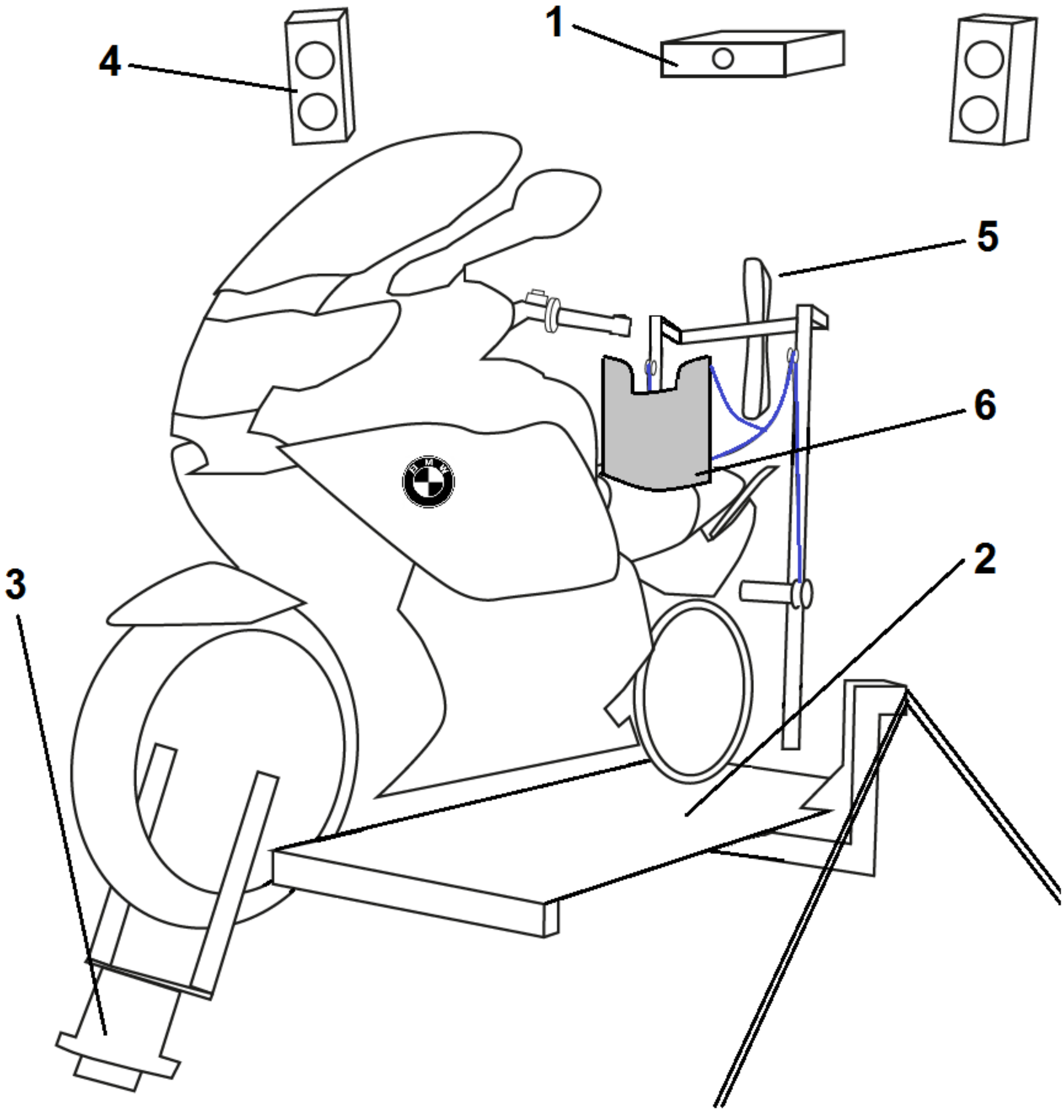

Figure 5-5.: BMW Motorcycle simulator with BMW K 1600 GT as mock-up and the most important systems that provide the virtual reality: 1 projector, 2 hexapod, 3 steering torque motor, 4 sound system, 5 traking system and 6 G-Vest

Figure 5-5 presents the motorcycle simulator at BMW Motorrad where this research is carried out. The mock-up consists of a BMW Motorcycle K 1600 GT and the virtual reality is provided by different systems; the most relevant ones are marked in figure 5-5 and are listed below: a projector (1) which provides the visual environment on a 4 by 3 m screen, a hexapod motion base (2) to simulate short-term accelerations, an electric motor (3) that reproduces steering torque, a 4.1 sound system (4) through which the simulator provides sound cues and the G-Vest (6), central element of this study, that provides long-term accelerations. In addition to all these systems, the simulator is equipped with a tracking system (5), which helps to measure the test rider's position.

5.2.3 Experimental scenarios

To verify the hypotheses, it is important that the participant concentrates on the actions of the G-Vest and that the study covers the most important situations of accelerating a motorcycle in real life. In this way there are three exercises that consist of an acceleration out of standstill to 50, 100 and 150 km/h followed by a deceleration on a straight section of a motorway without traffic.The final exercise is a free ride, where the participants rides on a rural road. The first, second and third exercise represent the speeding up in a city between traffic lights, on a rural road and on the highway, respectively. The fourth represents the accelerations and decelerations, road traffic, etc. The first three exercises are driven without traffic and permit that the participants concentrate on the actions of the G-Vest. However during the fourth exercise the participants should concentrate on more factors (corners, narrow road and road traffic) and not only on the G-Vest. Both scenarios are shown in figure 5-6.

Figure 5-6.: Left part: The motorway where the three first exercises are done. Right part: Scenario of the state highway

To allow the participants to compare the actions of the G-Vest each exercise consists on two trials: one time with the G-Vest and one time without.

5.2.4 Experimental procedure

The experimental protocol shown in figure 5-7 is designed for the purpose to minimize the simulator sickness related to a session in a simulated environment. It is generally recommended, that the training duration in the simulator last no longer than two hours and to take breaks (Kennedy et al., 1987).

On the basis of that information the research is planned to have an approximate duration of ninety minutes and it is divided in a presentation part and two blocs with a pause in the middle.

After a welcome and presentation of the study's aims, the participants are asked to sign a consent application and to answer the demographic survey (see appendix B, questionnaire 1) and the immersive Tendency questionnaire (standard questions (Scheuchenpflug, 2001)). Then they get all the particularities of the simulator explained and are asked to adopt a safe and reasonable speed and follow the guidelines given. After that, there is a free practice. They drive ten minutes without the G-Vest and ten minutes with it on a motorway with traffic. They are given the following directives to learn how the simulator reacts and allow to prepare the other tasks:

- Not to panic when the motorcycle model reacts different to a real one
- To drive without abrupt steering change. Like on a real road
- To accelerate and to decelerate to 0 km/h to train starting and stopping
- To ride slalom to get a better "feeling" of the lateral dynamics

The study consists of four experiments, each of which consist of two trials: one with the G-Vest active and one off. The order of the first three exercises as well as the option to begin (Trial 1) with or without G-Vest is randomized (see appendix A). The free ride (exercise 4) is left to the end to ensure that the participants have more experience with the simulator when riding on a rural road.

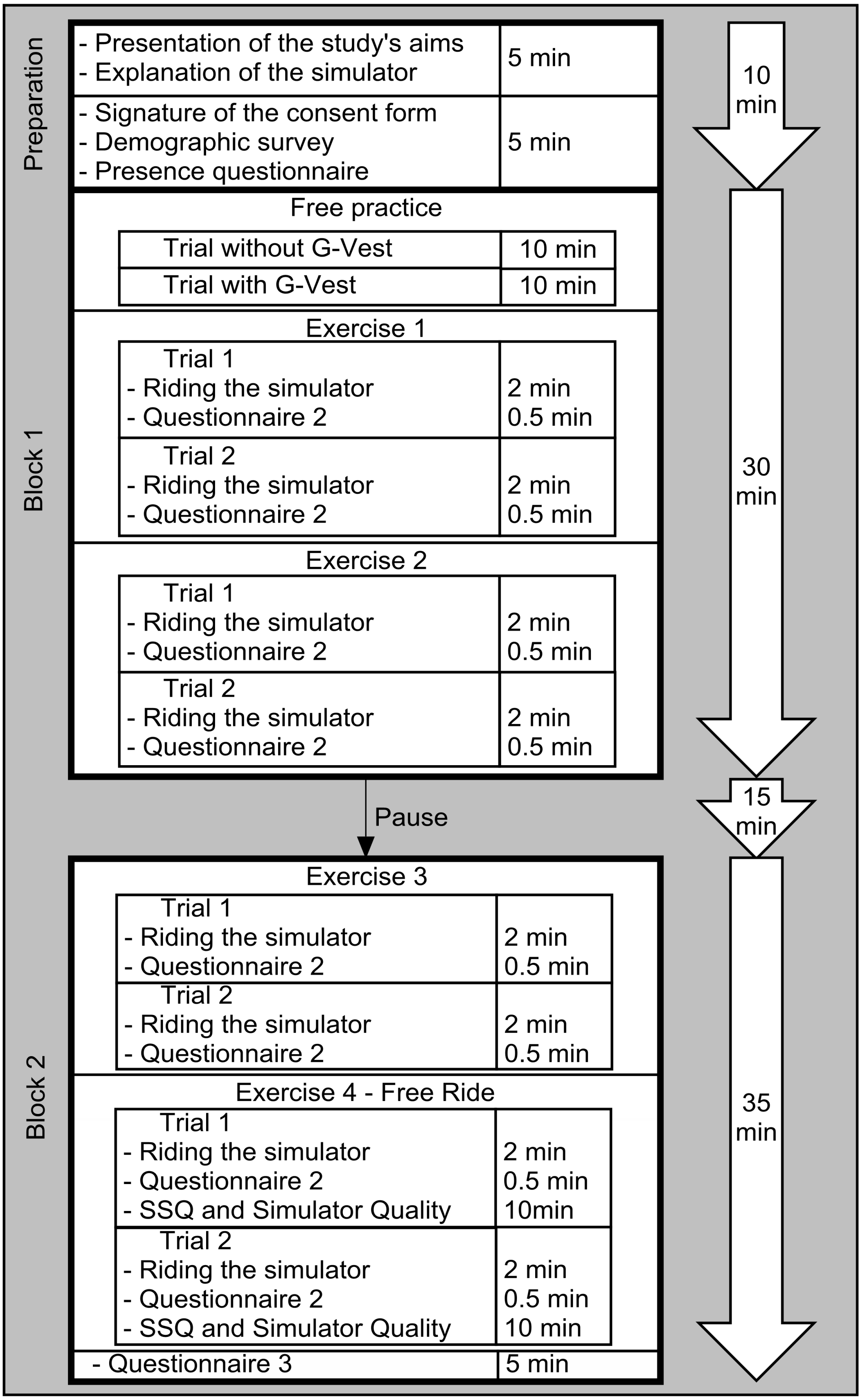

Figure 5-7.: Experimental procedure follow during the study. To see the questionnaires see appendix B.

After each trial the participants answer questionnaire 2 (see appendix B). In addition, after every trial of the free ride they answer the simulator sickness questionnaire (standard questions) and the simulator quality questionnaire (standard questions for BMW Motorrad). Finally, after completion of the four exercises they answer questionnaire 3 (see appendix B).

5.3 Results

The next pages show the data and results of the study, that help to confirm or reject the assumptions of this thesis. Figure 5-8 shows the definition of the boxplots used in the result of the study.

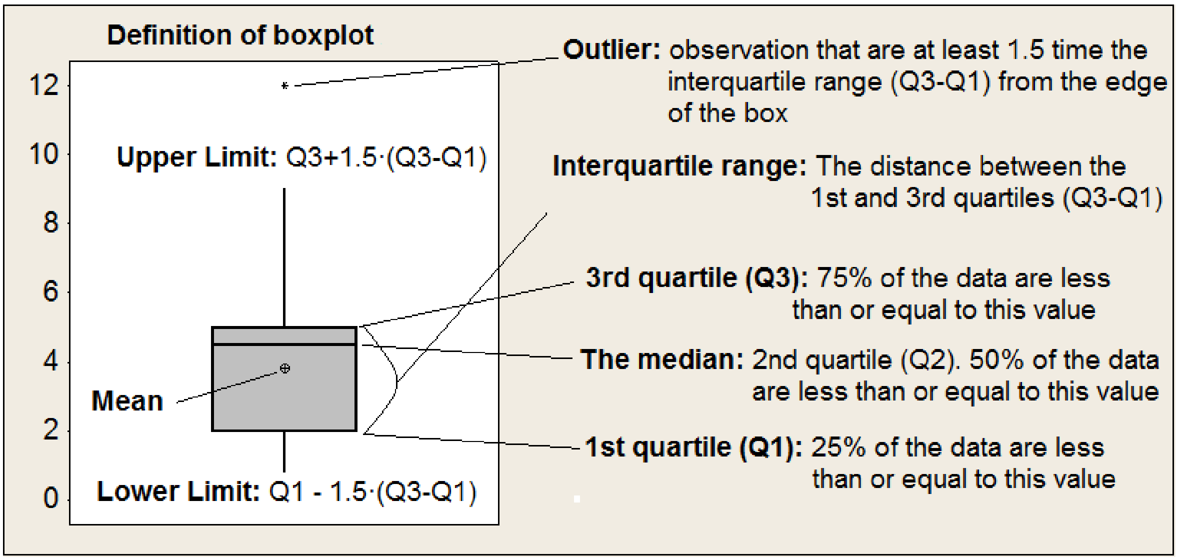

Figure 5-8.: Definition of boxplot used in the results

5.3.1 Assumption one: inertial force

The first hypotheses shows whether the inertial force can be represented by a pressure on the torso or not. For that reason the question: "*How realistically do you perceive the inertial force?*" with a possible answer from "*unrealistic=1*" to "*realistic=9*" is made at the end of each trial to the twenty participants.

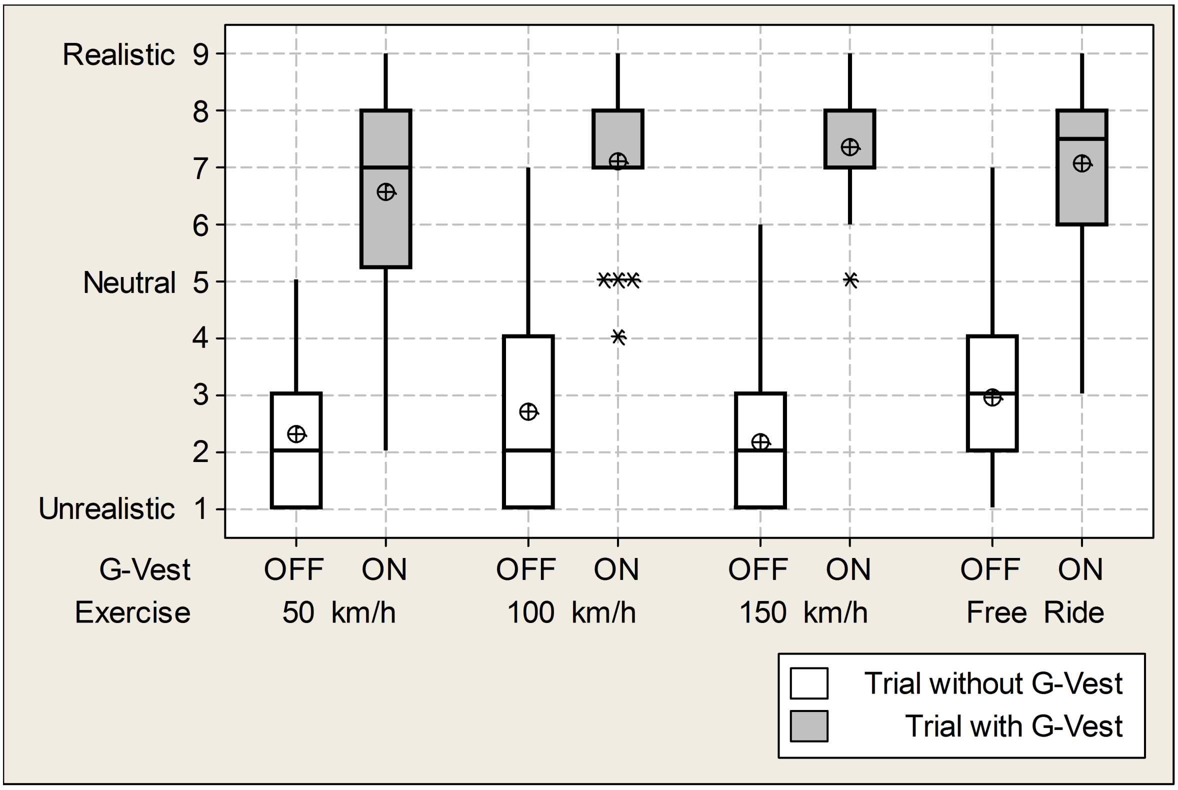

Figure 5-9.: Results of the inertial force question

Figure 5-9 presents the answers divided into the exercises and if the G-Vest was on or off. It can be observed that the perception of the inertial force is more realistic with the G-Vest, having median values in all the trials of the four exercises around seven (Realistic). Without it the median values are around two and a half (Not realistic). The results from all trials without the system have a minimum of one and a maximum ranging from five to seven. This values and the ones corresponding to first and third quartile can be observed in the figure. Finally, it should be noted that the dispersion with the G-Vest in exercises 50 km/h and free ride, is wider than in the other two ones. The unrealistic answer of exercise 50 km/h and free ride correspond to a participant who complained about the system. His problem is that one rope is out of the roll which it irritates him.

Because of the non-Gaussian distribution of the data, the Wilcoxon signed-rank test (Bortz, 2006) is used to verify statistically the difference between the median values corresponding to the trial with and without the G-Vest. The results are shown in table 5-2.

Exercise	p-value	h
50 km/h	$1.02 \cdot 10^{-06}$	1
100 km/h	$4.85 \cdot 10^{-07}$	1
150 km/h	$6.99 \cdot 10^{-08}$	1
Free Ride	$1.06 \cdot 10^{-06}$	1

Table 5-2.: Assumption One: Wilcoxon singned-rank test results

The test has been made for the four different exercises and the p-values obtained are low and with more than a 95% of confidence, the null hypothesis was rejected in favour of the alternative hypothesis which states:

The inertial force can be represented by a surface force on the torso.

5.3.2 Assumption two: airflow-induced forces

The second hypotheses, similar to the first one but with another force that the system represents, shows whether the airflow-induced forces can be represented by a surface pressure on the torso or not. For that reason the question: "*How realistically do you perceive the airflow-induced forces?*" with a possible answer from "*Unrealistic=1*" to "*realistic=9*" are made after all the trials to the twenty participants.

Figure 5-10 presents the results divided into exercises and whether the G-Vest was on or off. It can be observed that the difference between median values is not as big as the one with the inertial force. The median values with the G-Vest are around five and without it are around two. Moreover the free ride trial with G-Vest has a median of seven and a half, more realistic than the other three exercises. The dispersions in the exercise 150 km/h and free ride are wider than the other two. And in the exercise 150 km/h there is an outlier with a value of eight.

Here the data do not represent a Gaussian distribution, so the Wilcoxon signed-rank test is used to verify statistically the difference between the median values between the trials with and without the G-Vest.

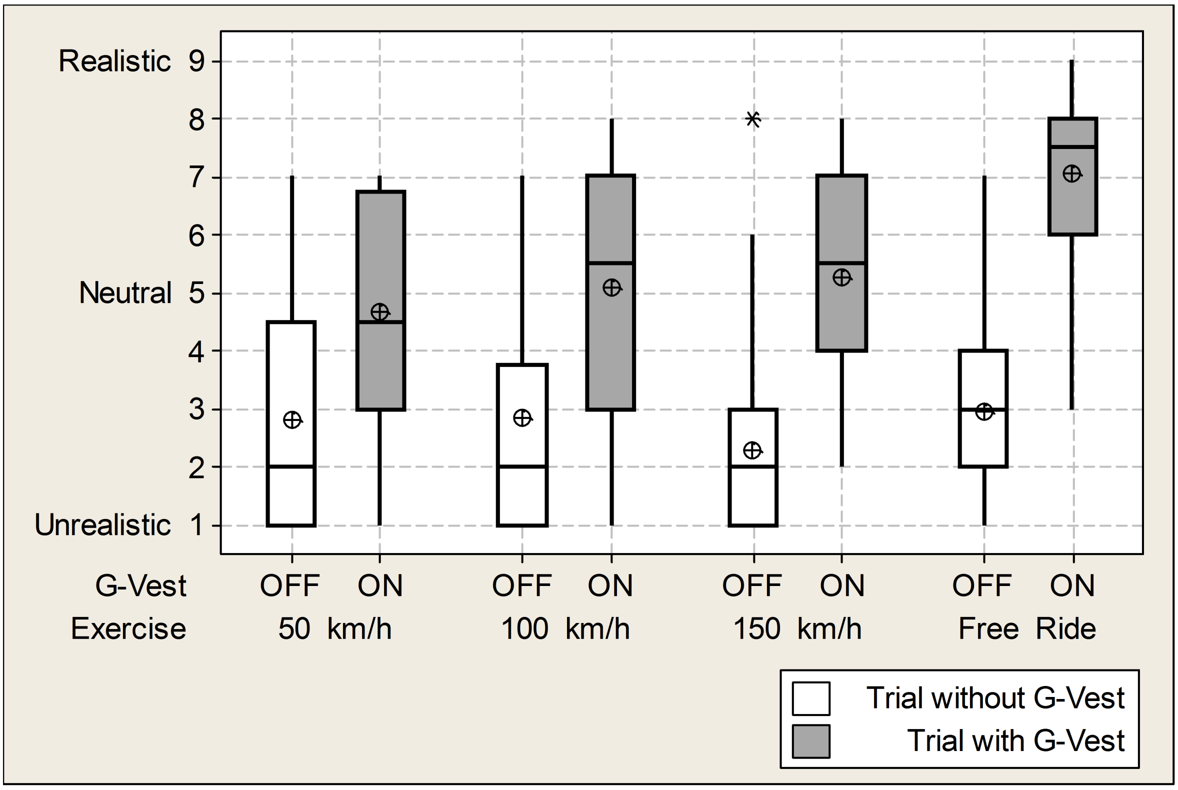

Figure 5-10.: Results of the inertial force question

Experiment	p-value	h
50 km/h	$5.08 \cdot 10^{-03}$	1
100 km/h	$2.08 \cdot 10^{-03}$	1
150 km/h	$4.26 \cdot 10^{-05}$	1
Free Ride	$2.70 \cdot 10^{-04}$	1

Table 5-3.: Assumption Two: Wilcoxon singned-rank test results

The test is made for the four different exercises and the p-values obtained are shown in table 5-4. With more than a 95% of confidence, the trials with G-Vest are more realistic than without it. The null hypothesis was rejected in favour of the alternative hypothesis which states:

The airflow-induced forces can be represented by a surface force on the torso.

5.3.3 Assumption three: perception of acceleration

The third hypothesis tries to find out if the perception of acceleration is realistic without exciting the vestibular system.

The data of the first question are analized to determine whether the median value is statistically hihger than five. The results are shown in table

Experiment	p-value	h
50 km/h	$3{\cdot}10^{-03}$	1
100 km/h	0	1
150 km/h	0	1
Free Ride	0	1

Table 5-4.: Assumption Three: Wilcoxon singned-rank test results

It can be is observed, than the median is bigger than five. Moreover, it can be seen visually on figure 5-9 that evaluation of the trials with the G-Vest is higher than five. That means that the perception of inertial force is realistic and therefore the perception of acceleration is realistic without exciting the vestibular system.

5.3.4 Assumption four: freedom of movements

The fourth hypothesis focuses on the freedom of movements with the G-Vest is guaranteed. For that reason, the movements of the participants in riding direction longitudinal (X), lateral to the right side (Y+) and Y to the left (Y-) side are saved and can be seen in figure 5-11 and 5-12.

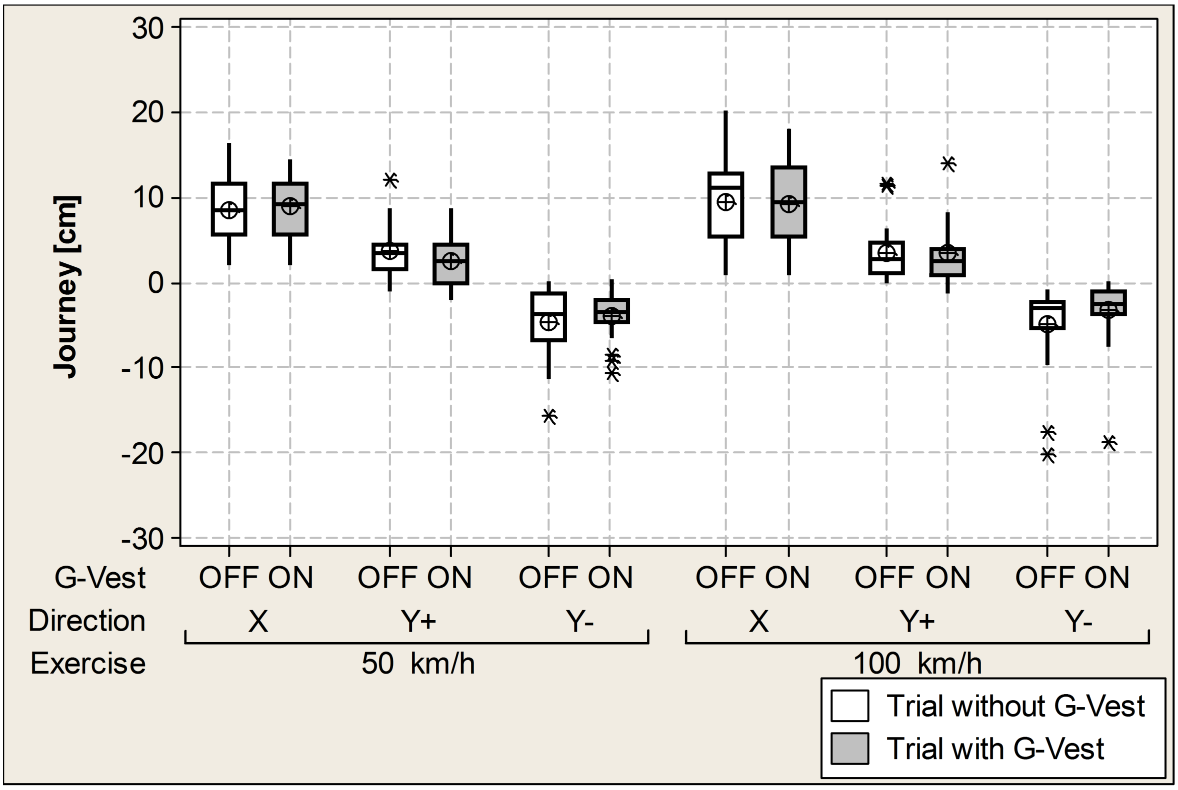

Figure 5-11.: Results of the participants' movements on the motorcycle for the exercises 50 and 100 km/h

As it can be observed in the image, the movement in X direction varies between the start position and twenty centimetres to the front with median values around ten. In the first three exercises the movement in Y direction vary between the null position and ten centimetres to the right and to the left with median values of three. The Y movements of the free ride exercise vary up to twenty-five centimetres. All the median values and dispersion between the different trials (with and without the G-Vest) for all the exercises in the study are similar.

Table 5-5 shows the results of the four exercises. All p-values are bigger than 0.05 fixed for the confidence interval. Moreover, it can be seen visually that the differences are

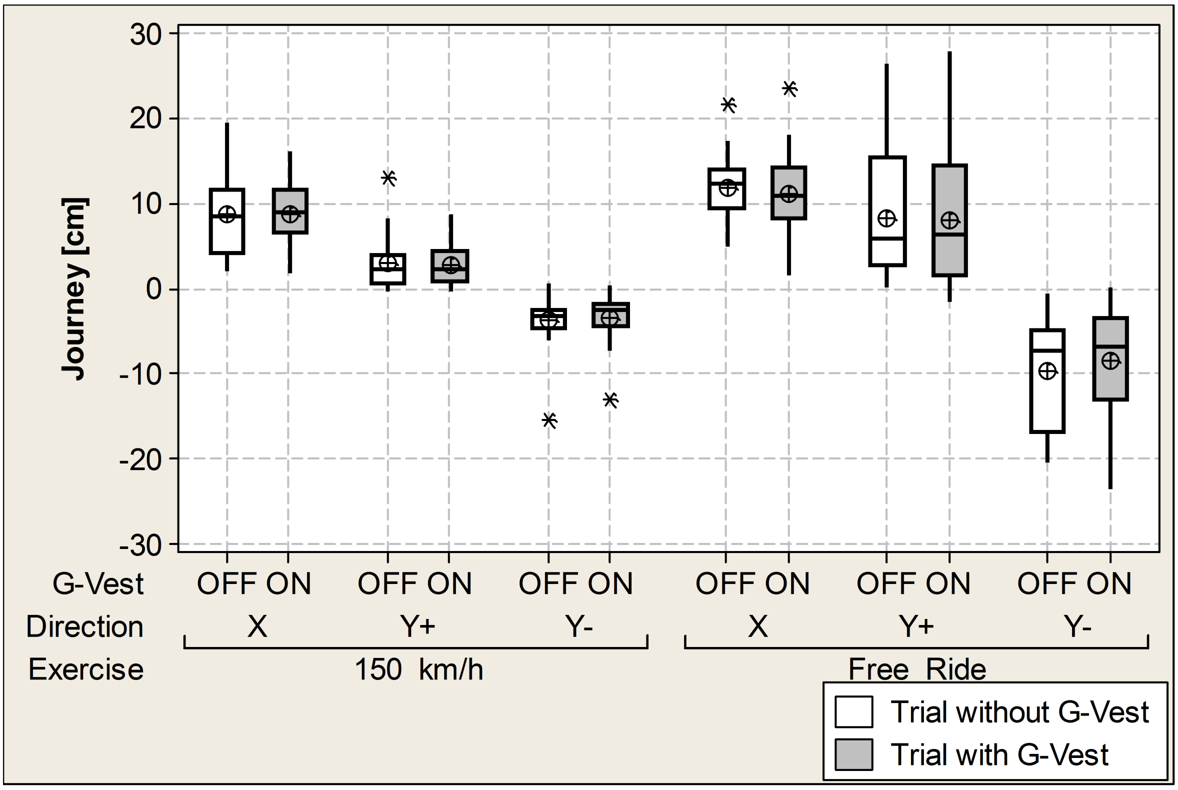

Figure 5-12.: Results of the participants' movements on the motorcycle for the exercises 150 km/h and free ride

	50 km/h		100 km/h		150 km/h		Free Ride	
Direction	**p-value**	**h**	**p-value**	**h**	**p-value**	**h**	**p-value**	**h**
X	0.598	0	0.797	0	0.989	0	0.579	0
Y to the right	0.508	0	0.839	0	0.797	0	0.903	0
Y to the left	0.882	0	0.209	0	0.457	0	0.525	0

Table 5-5.: Assumption Four: Wilcoxon singned-rank test results

due to the variability. That means that the null hypothesis is not refused and that the movements with the G-Vest are guaranteed.

5.3.5 Assumption five: Wearing comfort

Figure 5-13 shows the evaluation of the comfort of the system. For that reason the question: "Was the G-Vest comfortable?" with a possible answer from "*uncomfortable=1*" to "*comfortable=9*".

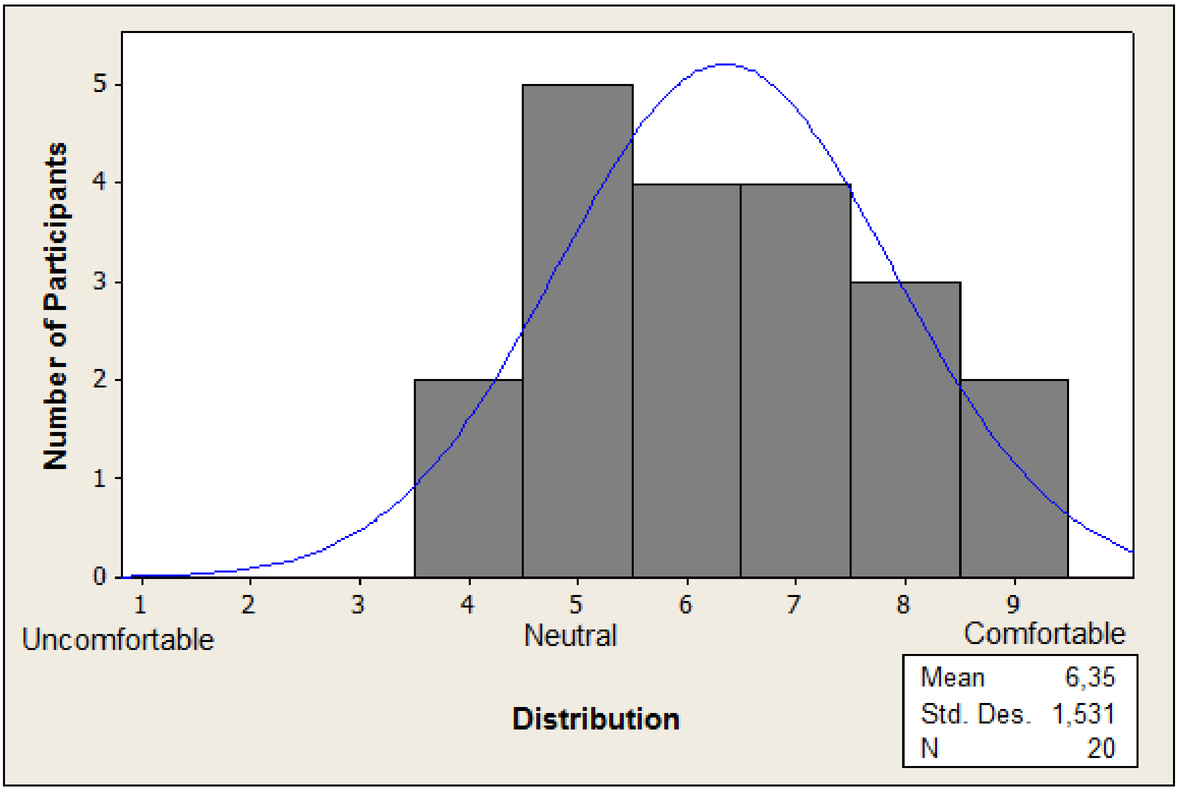

Figure 5-13.: Histogram of comfortability answers

The minimum evaluation of the invention is four and the maximum nine, being the mean value 6.35 and the standard deviation of 1.531. After the determination of the Gaussian distribution of the data, confirmed with a p-value of 0.191,the t-sample test is made. The result of this test is a p-value of 0.001 resulting the rejection of the null hypotheses and confirming that the G-Vest is a comfortable invention.

However, it is not so important to know only the evaluation, but the opinions of the people, collected in another question. Half of the participants think that the system is comfortable and it has not distract at them during the simulation. Nevertheless, some of them did constructive criticism that can be used in the future to improve the system. Among the complaints the only point to emphasise is that the vest was a bit loose and sometimes goes down, producing too much pressure in the stomach.

5.3.6 Other results

The next question is made to know about the opinion of the participants.
"*Did the lack of deceleration irritate you?*"
Possible answers: "*yes*" ; "*no*".

75.6 % of the participants are irritated because of the lack of a force that pushes forwards when braking the motorcycle.

5.4 Discussion

After presenting all the results, this section summarizes the hypotheses that have been accepted or rejected shown in table 5-6. Then there is a discussion about these hypotheses and the cause of these results.

The first hypothesis has an unequivocal result, and the rejection of the null hypothesis is clear. That means that the new invention can be used to represent inertial forces. The wide dispersion in the 50 km/h and free ride exercise may be a result of the lack of attention to the G-Vest. During the study, it became clear that the exercise 50 km/h is difficult for the participants because of the instability of a motorcycle during low speed and they cannot concentrate only in the system. During the free ride, the participants have to concentrate on more things than during the acceleration exercises like riding curves, watching for the traffic, speed limits, etc.

The second alternative hypothesis about airflow-induced forces is statistically accepted. However, the difference between the trials with the G-Vest on and off is not so clear. A possible reason can be that the ventilators are always on, and the value of this force is lower compared to the inertial force. That means that the difference between having this force or not is not so recognizable. In addition, the system only actuates on the torso, leaving out the head, where the airflow especially impacts. This fact has been remarked

Nº		Hypothesis	Result
1	H_0	The inertial force during riding a motorcycle cannot be represented by a surface force on the torso	Rejected
	H_1	The inertial force during riding a motorcycle can be represented by a surface force on the torso	Accepted
2	H_0	The airflow-induced forces cannot be represented by surface forces on the torso	Rejected
	H_1	The airflow-induced forces can be represented by surface forces on the torso	Accepted
3	H_0	The perception of acceleration riding a motorcycle is unrealistic without exciting the vestibular system	Rejected
	H_1	The perception of acceleration riding a motorcycle is realistic without exciting the vestibular system	Accepted
4	H_0	The freedom of movements whit the G-Vest is guaranteed	Accepted
	H_1	The freedom of movements with the G-Vest is not guaranteed	Rejected
5	H_0	The G-Vest is uncomfortable	Rejected
	H_1	The G-Vest is comfortable	Accepted

Table 5-6.: Summary of the hypotheses testing

by some participants explaining that it would be a good completion to the invention. They said that they also expect a force on the head from the airflow.

Once the first assumption (the inertial force during riding a motorcycle can be represented by a surface force on the torso) has been proved, it makes sense to speak about the perception of acceleration. The acceleration depends directly on the inertial force. If the representation of the force is not realistic than the perception of acceleration cannot be realistic. However, the representation of the inertial force is realistic and therefore the perception of acceleration is realistic without exciting the vestibular system.

The results show that the freedom of movements with the G-Vest is guaranteed and the null hypothesis is accepted. It is an important point not to prejudice some characteristics of the simulator looking for the improvements of other ones. All the people were satisfied with the mobility of the system: their movement was not limited by the system.

Finally, it can be noticed that the invention is comfortable, with a high ranking (mean of 6.35), but there are changes that can be made according to the suggestion of the people. They pointed out that, though it was comfortable, the vest is a bit loose producing sometimes too much pressure on the stomach by slipping down.

6 Conclusions

This thesis covers the construction, calibration and integration of the system in the BMW Motorrad simulator and the conduction of a research study to prove the functionality of the G-Vest.

The research carried out on the human's perception of acceleration, on the acceleration systems used in other types of simulators and the study of motorcycle simulators through history has resulted in a system that provides long-term accelerations on motorcycle simulators without moving the rider.

When accelerating a motorcycle an inertial force (volume force) is produced that pushes the rider backwards. Moreover there are airflow-induced forces when riding a motorcycle depending on the velocity. The G-Vest represents both forces through a pressure on the torso of the rider. There are some simplifications between reality and the simulation: the representation of a volume force through a pressure, the concentration of the airflow-induced force on the torso and the missing stimulation of the vestibular system.

The G-Vest consists of a vest with a big contact surface, which distributes the forces and avoids punctual pressures. This vest is actuated by electric motors, which create a force backwards. The system could easily be integrated into a motorcycle simulator like the one at BMW Motorrad.

Twenty participants took part in a study in which they reproduced three accelerations up to a velocity of 50, 100 and 150 km/h and a free ride with and without the G-Vest active. Firstly, the results induced by the G-Vest showed that the inertial and airflow-induced forces can be represented by a surface pressure on the torso. However, the perception of airflow-induced forces could be more realistic and the system could be upgraded at this point. Secondly it was also proved that the perception of acceleration can be realistic without exciting the vestibular system. And finally, it was clarified that it is a comfortable device which does not restrict the freedom of movements on the motorcycle. Therefore, this work confirms our idea, where the G-Vest is the starting point in the representation of long-term accelerations on motorcycle simulators.

7 Future Work

Through the work of research and development of the G-Vest, different paths have been opened to optimize and extend it.

The device can be expanded to include the simulation of the deceleration. The research has demonstrated the effectiveness of the G-Vest installed on the back of the rider for the simulation of accelerations. Moreover, the participants are irritated, because of the lack of a braking force. Hence, the development of a similar mechanism that could act on the frontal part of the rider would allow to simulate decelerations and improve the control of the forces on the rider. However, in the front part of the motorcycle there is not so much space, so it would be recommendable to take care about it not to disturb the visibility. One solution is to attach a rope to the bottom part of the bike, where the motor can be placed, or to place the system in the fairing.

In the case of the system, some changes can be made to improve the device. The airflow-induced forces' sensation can be ameliorated by using bigger ventilators that increase the airflow. Moreover, the ventilators should be controllable, permitting their regulation depending on the velocity. Another improvement for the airflow-induced forces' sensation is the creation of a machinery that pulls the head backwards. However, since it is a free joint and a delicate part of the body, the force should not be high and the system ought to have a damping. A starting point could be a suction cup, which is easy to adapt to all helmets.

Furthermore, another point to improve is the replacement of the vest with an integral harness that is fixed to the rider and which prevents the slide of the vest. The harness does not compromise the comfortability of the system and it allows the anchorage from the front and back parts.

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A Latin Square method

To have independent results the order of the task was designed using that latin square method. Table 1-1 shows the sequence for all test people. The first number indicates the exercise and the second says whether the trial one starts with or without the G-Vest.

Participant	First task	Second task	Third task	Fourth task
01	50-ON	150-OFF	100-ON	FR-OFF
02	100-ON	150-ON	50-OFF	FR-OFF
03	150-OFF	50-OFF	100-ON	FR-ON
04	50-OFF	100-ON	150-ON	FR-ON
05	150-OFF	50-OFF	100-ON	FR-ON
06	50-OFF	100-OFF	150-OFF	FR-ON
07	100-OFF	150-OFF	50-OFF	FR-ON
08	150-ON	50-OFF	100-OFF	FR-OFF
09	150-OFF	100-OFF	50-OFF	FR-OFF
10	10-OFF	50-OFF	150-ON	FR-OFF
11	50-OFF	150-OFF	100-ON	FR-ON
12	50-ON	150-OFF	100-ON	FR-OFF
13	100-OFF	150-ON	150-OFF	FR-ON
14	100-OFF	150-ON	150-ON	FR-OFF
15	150-OFF	100-OFF	50-OFF	FR-OFF
16	100-OFF	50-ON	150-ON	FR-OFF
17	50-ON	150-OFF	100-ON	FR-OFF
18	100-ON	150-ON	50-OFF	FR-OFF
19	100-OFF	50-OFF	150-OFF	FR-ON
20	100-ON	50-OFF	150-ON	FR-OFF
21	150-OFF	150-ON	100-ON	FR-ON
22	100-ON	50-OFF	150-OFF	FR-OFF
23	100-OFF	150-ON	150-OFF	FR-OFF

Table 1-1.: Participant’s task sequence

B Questionnaire

Questionnaire 1 (Demographic survey)

<table>
<tr><td colspan="5">Age</td></tr>
<tr><td colspan="5">Gender</td></tr>
<tr><td colspan="2">Female</td><td colspan="3">Male</td></tr>
<tr><td colspan="5">Profession</td></tr>
<tr><td colspan="5">Driving Licence A (Motorcycle): ... years</td></tr>
<tr><td colspan="5">Are you right or left handed?</td></tr>
<tr><td colspan="2">Right-handed</td><td colspan="3">Left-handed</td></tr>
<tr><td colspan="5">How many km do you drive with the motorcycle?</td></tr>
<tr><td><5000 km</td><td>5000-10000</td><td>10000-20000</td><td colspan="2">>20000</td></tr>
<tr><td colspan="5">What motorcycle do you used normally (brand/type)?</td></tr>
<tr><td colspan="5">Are you colour blindness?</td></tr>
<tr><td colspan="2">No</td><td colspan="3">Yes</td></tr>
<tr><td colspan="5">Do you need help to drive?</td></tr>
<tr><td colspan="2">No</td><td colspan="3">Yes</td></tr>
<tr><td colspan="5">Compared to other motorcyclist I would rate me as...</td></tr>
<tr><td>1=unexperienced</td><td>2</td><td>3=neutral</td><td>4</td><td>5=experienced</td></tr>
<tr><td colspan="5">Compared to other motorcyclist I describe myself as...</td></tr>
<tr><td>1=tranquil</td><td>2</td><td>3=neutral</td><td>4</td><td>5=sporty</td></tr>
</table>

Table 2-1.: Questionnaire 1 (Demographic survey)

Questionnaire 2

After each task the questions showed in table 2-2 were asked.

<table>
<tr><td colspan="9">Q1: How realistic do you perceive the inertial force?</td></tr>
<tr><td>1=unrealistic</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td>8</td><td>9=realistic</td></tr>
<tr><td colspan="9">Q2: How realistic do you perceive the airflow-induced force?</td></tr>
<tr><td>1=unrealistic</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td>8</td><td>9=realistic</td></tr>
<tr><td colspan="9">Q3: How realistic do you perceive the combination of both?</td></tr>
<tr><td>1=unrealistic</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td>8</td><td>9=realistic</td></tr>
<tr><td colspan="9">Q4: The simulated acceleration was compared to the expected one...</td></tr>
<tr><td>1=less</td><td>2</td><td>3</td><td>4</td><td>5=suitable</td><td>6</td><td>7</td><td>8</td><td>9=stronger</td></tr>
<tr><td colspan="9">Q5: Did the lack of deceleration irritiert you?</td></tr>
<tr><td colspan="4">Yes</td><td colspan="5">No</td></tr>
</table>

Table 2-2.: Questionnaire 2

Questionnaire 3

Table 2-3 show the questions maked at the end of all the exercises.

<table>
<tr><td colspan="9">Has the G-Vest restricted your movements?</td></tr>
<tr><td>1=No</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td>8</td><td>9=Yes</td></tr>
<tr><td colspan="9">Was the G-Vest comfortable?</td></tr>
<tr><td>1=uncomfortable</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td>8</td><td>9=comfortable</td></tr>
<tr><td colspan="9">Explain why the G-Vest is uncomfortable or comfortable</td></tr>
<tr><td colspan="9">Compared the ride with and without the G-Vest:
Which ride is more realistic?
Which ride do you like more?
Which ride do you like to repeat?
Which ride permits you more movements?</td></tr>
<tr><td colspan="3">Without G-Vest</td><td colspan="2">Same</td><td colspan="4">With G-Vest</td></tr>
<tr><td colspan="9">During the acceleration of a motorcycle high inertial forces actuate on the rider,
which push him/her backwards. In order not to fall of the bike during acceleration process it is
necessary to support this inertial forces. What is your strategy to support these forces?</td></tr>
<tr><td colspan="9">I hold the handlebars firmly in order not to fall back
I tension legs, back, and abdominal muscles in order not to fall back
I combine both possibilities
Another answer</td></tr>
<tr><td colspan="9">Is this the same strategy that you use during real journeys?</td></tr>
<tr><td colspan="4">Yes</td><td colspan="5">No</td></tr>
</table>

Table 2-3.: Questionnaire 3