# PROTOTYPING OF A WEARABLE DEVICE AND EXPERIMENTAL EVALUATION OF THE EFFECT OF LIGHT TOUCH ON HUMAN POSTURAL STABILITY

handed in
MASTER'S THESIS

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MASTER'S THESIS
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## Prototyping of a Wearable Device and Experimental Evaluation of the Effect of Light Touch on Human Postural Stability

Problem description:

When our body balance is disturbed or unstable in everyday life, we will get dependent on support e.g. by another individual to prevent bodily injury. It has bee been shown that human body balance can be improved by light touch (<1N) with a static surface [1] as well as by being in light touch with another person [2]. Although, in everyday life these methods are not always applicable, as it is hard to provide light touch with a static surface for activities of daily living, as well as to provide enough care givers for interpersonal support. Consequently, alternative aids for individuals with disturbed postural control are needed to prevent falls while at the same time maintaining the patient active and as independent as possible. Therefore, the effect of various light touch stimuli applied by a wearable device at the wrist should be analysed within this research topic.

Tasks:

- Literature research,
- Adapt the design of existing prototype,
- Implement different light touch stimuli,
- Implement synchronisation of stimuli given and data captured,
- Answer the following research questions:
    Can a wearable device at the wrist improve body sway?
    Is the effect of the body-fixed references comparable with the effect of an earth-fixed reference?
    How does the type of stimulus affect the body sway?

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[2] L. Johannsen, A. Guzman, and A. Wing. Interpersonal light touch assists balance in the elderly. *Journal of motor behavior*, 41:397–9, 06 2009.

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# Abstract

*Background*: Haptic stimulation of a light touch may prevent elderly from fall. A wearable device could provide such haptic stimuli.

*Objective*: Light touch of an earth fixed reference point, performed on different parts of the body, reduces postural sway. From different studies I assume that a light touch provided by a wearable device can also reduce the body sway. In this study, I hypothesize that different haptic stimuli provided by a wearable device, can reduce postural sway.

*Methods*: Balance of 4 healthy younger adult students (female n=2, male n=2) aged 26±1.15 years were measured under six conditions on a force plate. The subjects stood in an upright bipedal position with 5 cm inter heel distance, arms relaxed hanging down and eyes closed for 30 s per trial. For control condition (cc) the subjects were without treatment. During condition of constant vibration (cv) an own designed wearable haptic device performed a light touch with $\leq$ 1 N and constant vibration (150 Hz), during condition device off (do) the subjects wore the device without a haptic stimulus, the condition sinusoidal force (sf) generated a sinusoidal (0.3 Hz) contact force of $\leq$ 1 N, the condition sinusoidal vibration (sv) produced a sinusoidal (0.3 Hz) vibration (150 Hz) at a contact force of $\leq$ 1 N and during condition earth fixed (ef) the subjects had an earth fixed reference point of $\leq$ 1 N at the wrist. The wearable haptic device was worn like a watch on the wrist. Body sway parameters rambling and trembling in medial-lateral and anterior-posterior direction as well as the COP-velocity were analysed.

*Results*: Overall no significant results were found. However, a descriptive analysis showed a relatively clear reduction for condition (ef) compared to (cc) for parameters rambling in medial-lateral, trembling in medial-lateral and anterior-posterior as well as for COP-velocity. These results were confirmed by significant differences of individual subjects. Light touch stimuli (cv) and (sf) of the wearable device showed minimal decreasing effects for rambling in medial-lateral, trembling in medial-lateral and anterior-posterior and for COP-velocity. The stimulus (sf) showed a slightly reduced effect for the parameters trembling in medial-lateral direction and for COP-velocity.

*Conclusion*: Even though the results were not significant, probably because of a small sample size (n=4), I assume (ef) had a reducing effect on body sway. For the haptic stimuli of the wearable device I suspect a reducing effect. This must be verified with a larger sample. Perhaps elderly people show a greater effect than young healthy adults.

# Contents

# Chapter 1

# Introduction

In the light of increasing numbers of elderly people in industrial developed countries [Bun19] health becomes more important. Fall prevention plays a major role because most accidents are condemned by falls [KI13]. For people over 60, falls are responsible for more than half of all accidents at home (54.4 %) [ibid.]. Alternative mobility aids of Wheeled Walker (WW), canes and crutches become more relevant since urban living with little space gets more expansive and elderly are not satisfied with common mobility aids [BIS03]. According to the decrease of human postural sway by light touch at the finger tip [JR94], haptic stimuli at the human wrist might also be able to reduce body sway and be a potential stability and mobility aid for everyday life.

Human upright stance is a demanding task by considering its countless degrees of freedom and limited sensory sources [TB14]. Sensory cues from somatosensory, visual and vestibular systems have to be integrated in the central nervous system to accomplish and maintain adequate postural orientation [AKJ06]. Furthermore the effector system uses these information to contract the muscular system [Nas81].
Visual, proprioceptive and vestibular signals are the primary sensory inputs for postural control [Nas81]. Additionally, somatosensory information have an influence on postural control. Hereby, especially mechanoreceptors of the skin, contribute to proprioception [DDGM84] [EK01]. On the one hand somatosensory stimulation by a vibrotactile stimulation of the hands or feet can elicit illusions of body motion in blindfolded subjects. On the other hand somatosensory information of the fingertip can reduce postural sway. [BIS03] [LD84]. A non-physical supporting fingertip contact to an external earth fixed reference provides orientational information to find postural equilibrium [JSD97]. Jeka and Lackner [JR94] showed, that the nearly in-phase relationship between body sway and fingertip contact forces implies that fingertip contact forces are used to offset physically movements of the body's centre of mass (COM) during force contact conditions. A specification of different mechanoreceptors contribution in the fingertip and its stimuli has not been investigated in relation to postural sway.

According to the World Health Organization (WHO), there are over 400 relevant fall risk factors [Org07]. The use of canes and frame/elbow crutches is a significant ($p<.001$) risk for people of 70 years and older to fall [CBS89]. Even a WW, used to improve balance and mobility [BM05], [SBS+09] as well as to protect from falling of older people [GLW+03], makes them more likely to sustain a severe injury when falling, e.g. a hip fracture [vRHP+13]. Many users of WW are not satisfied in all respects of usage and especially woman, users living alone and first time users are likely to be dissatisfied. The main problem identified is handling the WW and for several users the physical environment caused accessibility problems [BIS03]. Due to previously reported problems it can be assumed that elderly, especially when something has to be done quickly, do not use mobility aids. Nocturia and incontinence, especially urge incontinence, cause a rush to the toilet. The patient often does not use compensatory interventions for a safe gait, which further increases the incidence of falls [PF07]. A constantly worn device could solve the comfort problem of not choosing a supporting system and provide a mobile aid.

There is a lack of research in the use of touch contact for balance control, which has not been studied systematically or rigorously [Jek97]. Specially the large population of elderly people may have potential with light touch contact and postural control [ibid.]. For this reason the overall goal of this work is to analyse the effect of light touch on the wrist, provided by a wearable device to provide one of the first steps for new technology. A rough structure to achieve this goal can be seen in figure 1.1.

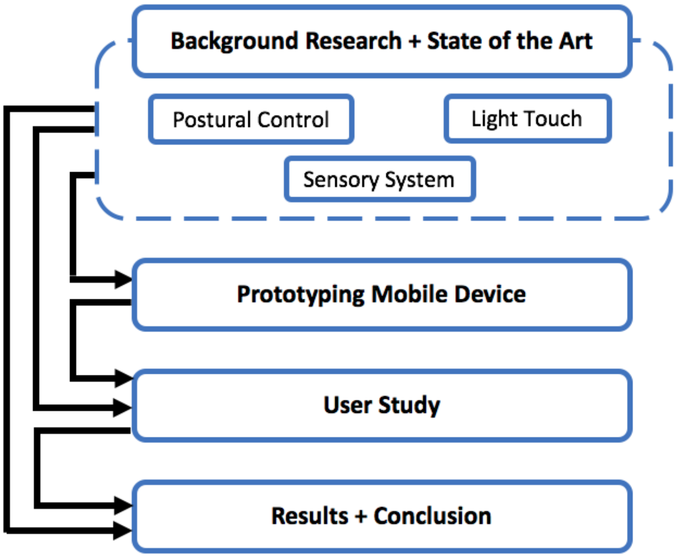

Figure 1.1: Rough structure of the work and presentation of the most important interrelationships

# Chapter 2

# Background Research

The following chapter provides an overview of the theoretical framework of this study. This helps the reader to better understand the study content. The present thesis deals with the investigation of the relationship between light touch stimuli and their effect on postural sway. For this reason I will explain the sensorimotor system, which is in its complexity responsible for the human upright stance. The focus is on the sensory system and the involved receptors as well as their excitation and conduction as I investigate the influence of stimuli. Subsequently, I explain the processes of motor control, the upright stance and its measured terminologies. At least I turn the focus on the forearm in its anatomy.

## 2.1 The Sensory System

The human body is permanently dependent on the sensory system, which receives signals from the organism and processes them in the central nervous system (CNS) [PG12]. Absorption and processing of stimuli enables the human being to react quickly and appropriately to the environment and obstacles in it [ibid.]. Thus, the sensory system plays a decisive role in the control of movement, the so-called sensorimotor system as illustrated in figure 2.1. The sensorimotor system, a subcomponent of the body's comprehensive motor control system [RL02], is extremely complex and consists of the interaction between the sensory system and the active locomotor system [Lau09]. The neuronal input, which comes from peripheral receptors and the visual and vestibular system, is integrated in the CNS and thus generates a motor response [LPGF97]. For example, it is impossible to achieve a given goal without input and feedback from the visual or proprioceptive system [PG12]. In contrast, sensor technology describes the process of sensory perception and transmission to the CNS [Bir10].
In order to understand the complexity of postural control, I present all sensory systems involved. The reception of sensory information is done by receptors, which are explained in detail in the following subsections.

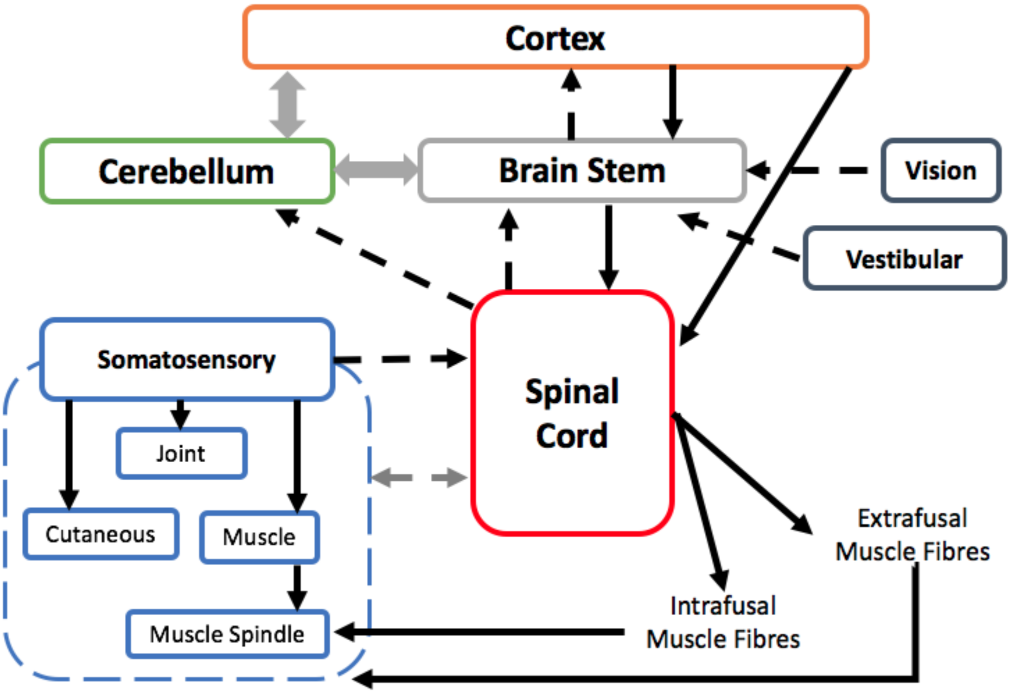

Figure 2.1: The sensorimotor system incorporating all afferent, efferent and central integration and processing components. Afferent pathways (dotted lines), efferent pathways (solid lines) and reflexes (dotted grey lines) as well as descending motor commands (grey lines). Figure adapted by [RL02].

### 2.1.1 Receptors

Receptors are the sensors of the human body that serve to absorb stimuli [FS16]. Each receptor responds optimally to one stimulus, the *adequate stimulus*. We speak of an adequate stimulus when a physical or chemical stimulus leads to a change in the membrane potential under minimal energy input in order to excite the organ in question [GS17]. This stimulus is defined by the stimulus quality, strength and duration [Lau09]. The specific sensitivity of the stimulus is enabled by the membrane properties of the sensors and the construction of the sensory cells [Zim19]. Depending on the location of the receptors, they are differentiated into exteroceptors, enteroceptors and proprioceptors [Lau09]. All mechanoreceptors can be seen in table 2.1 at the end of this section.

*Exteroceptors* take up stimuli from the environment. Exteroceptors include mechano-, chemo-, thermo- and photoreceptors as well as nociceptors. The receptors are named according to the quality of perception, which diverge in mechanoreceptors (pressure, tension, vibration, strain, shear, sound waves), chemoreceptors (ions, osmolarity, tissue hormones, scents), thermoreceptors (cold, heat), photoreceptors (light) and nociceptors (pain) [Lau09]. Further information regarding the quality of perception of receptors and their function can be found in Laube [Lau09] p. 45.

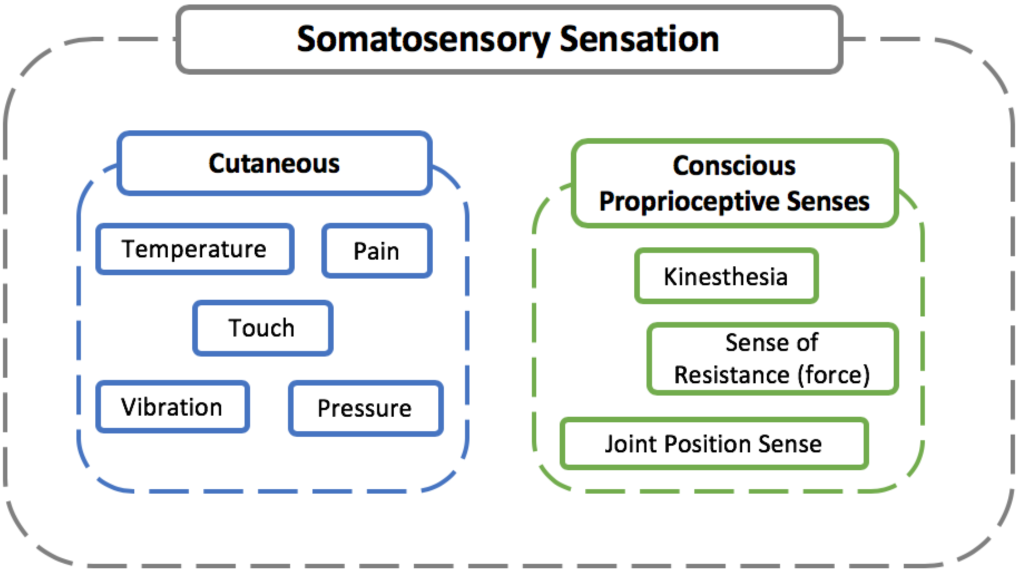

Figure 2.2: Sensations arising form somatosensory sources. Figure adapted by [RL02].

*Enteroceptors* provide information about mechanical and chemical processes in the intestines [Bir10]. This information about the internal organs is sent by baro- and chemoreceptors [Bir10].
*Proprioceptors* serve to determine the position and positional changes of the body in space [Lau09]. Proprioception is defined as a sense that includes both joint movement (kinaesthetic) and joint position (sense of position) [LPGF97]. In comparison, Riemann and Lephart [LPGF97] divide proprioception into three sub modalities: sense of movement (kinaesthetic), sense of position (joint) and force, which can be seen in figure 2.2. This perception is ensured by mechanoreceptors of the skin, muscles and joints [PG12]. All receptors provide information which is referred to as the *somatosensory system*, which can be seen in figure 2.2. Another component of proprioception is the vestibular organ, which belongs to the secondary sensory cells as well as the visual system [Bir10].
Since the present study deals with the cutaneous mechanoreceptors of exteroception and proprioception, the focus is on these. Additionally I present the Muscle spindle and the Golgi tendon organ, which play an important role to maintain postural control. Mechanoreceptors convert mechanical stimuli into electrical signals, which are processed in the CNS and contribute to perception. They are located in the skin (cutaneous sensitivity), in joint capsules, ligaments, fascia, tendons and muscles (proprioception) and in the internal organs (enteroception) [Lau09]. Subcutaneous mechanoreceptors can be divided into intensity, tactile and vibration sensors [Bir10, Lau09]. The *intensity sensors* type I are slowly adapting Merkel cells (A$\beta$) [1], which are located in the deep layers of the epidermis of glabrous skin. The counterpart to the Merkel cells in the

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[1] The level of myelination and the diameter of the axon are explained in subsection 2.1.2

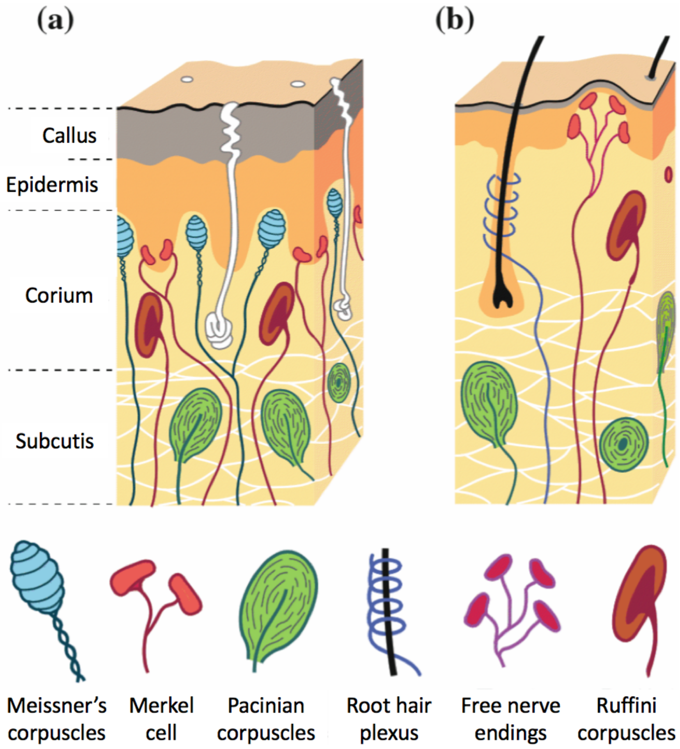

Figure 2.3: Histology of mechanoreceptors in (a) glabrous and (b) hairy skin. Figure adapted by [Sch10].

glabrous skin are free nerve endings that reach right below the surface of the glabrous skin [Bir10]. The location of all mechanoreceptors of the skin is shown in figure 2.3. Sensor type I is vertically pressure-sensitive and detects both the intensity and duration of the pressure due to its slow adaptation behaviour [Bir10]. In contrast, the intensity sensor type II, the Ruffini corpuscles (A$\beta$), is pressure and strain sensitive and detects shear forces [Lau09]. As a result to the slow adaptation, the Ruffini corpuscles are called dynamic and static receptors [RL02]. By the reason to the perception of shear forces, Ruffini corpuscles can detect shifts between tissue layers in glabrous as well as hairy skin. These tissue shifts take place during joint movements, so that Ruffini corpuscles additionally contribute to proprioceptive perception [Bir10]. Consequently, Ruffini corpuscles are sensors of depth and surface sensitivity, as they detect pressure, tension and joint movements [Lau09, Bir10]. The intensity and time course of the mechanoreceptors in glabrous skin caused by a stimulus and answered by the neural spike train can bee seen in figure A.1 in the appendix.

The *tactile receptors* consist of the rapidly adapting Meissner's corpuscles (A$\beta$) of the glabrous skin and the Root hair plexus (A$\beta$) of the hairy skin, which also adapt rapidly. These receptors register hair movement and „variable stimulus intensities triggered by movement " [Lau09] such as vibrations (3 - 40 Hz), stimuli of movement and skin deformations. The last group are the *vibration detectors* or vibratory sensors. They can be

found in hairy and glabrous skin as well as in tendons, fascia, muscles, periosteum and joint capsules and are called Pacinian corpuscles (A$\beta$) [Lau09]. They perceive vibrations in the high frequency range (100-300 Hz), as seen in figure 2.4 and belong to the fast adapting sensors [Bir10, GBH$^+$94]. As a result of their adaptive behaviour, the Pacinian corpuscles are assigned to the dynamic receptors [RL02]. Due to the position of Pacinian corpuscles, they belong to both the cutaneous and proprioceptive system.
The corpuscular endings of the mechanoreceptors are very unevenly distributed over the human body surface [SS06]. This is particularly evident on the hand. A whole range of different mechanoreceptors, including those of proprioception from deeper tissue layers, are activated when objects are palpated [PKS14]. For the fine recognition of surfaces only Merkel (SA I) and Meissner corpuscle (RA) play a central role in the fingertip [ibid.]. The information from these mechanoreceptors is transmitted almost one-to-one to the cerebral cortex, which I explain in the later subsection 2.1.2.

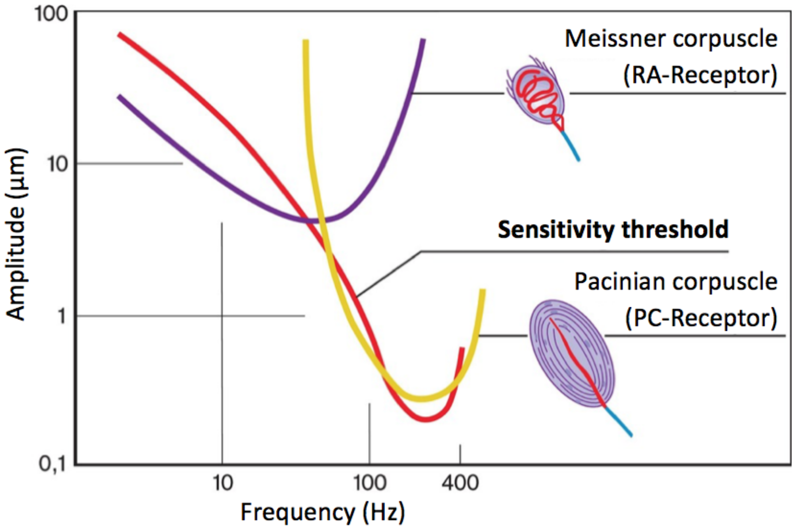

Figure 2.4: Sensory threshold and stimuli threshold of Meissner corpuscles and Pacinian corpuscle of the hand by [PKS14].

So far, the Ruffini and Pacinian corpuscles are already known as components of proprioception. These are mainly located in the joint capsule and other connective tissue joint structures such as the anterior cruciate ligament [Lau09]. These joint receptors can be divided into position, movement, end movement and damage detectors [ibid.]. In general, joint receptors provide information regarding joint position, change and speed [PG12, Lau09]. Other mechanoreceptors of proprioception are the Muscle spindle and Golgi tendon organ [Lau09].

*Muscle spindles* are length receptors arranged parallel to the working muscles [Ill08]. They serve to monitor and stabilise the length of a muscle and are popularly characterised as protection against over stretching. The muscle spindle consists of a sensitive middle part (Ia afferents) and two contractile endings (gamma-activity) [ibid.] as seen in figure 2.5. Since length receptors are fused with the extrafusal muscle fibres of the surrounding muscle, the muscle spindle follows the stretching of this muscle [ibid.]. As a consequence, the Ia and II3 afferents send information about length status of the muscle via alpha-motor neurons [SLH11]. Consequently, the agonist is activated with the aim of length stabilization, which is limited by an inhibitory interneuron (reciprocal inhibition) [ibid.]. To ensure the sensitivity of muscle spindles, they are kept under tension via the contractile ends, independent of the activity of extrafusal fibres (gamma-activity) [Ill08, RL02]. This gamma-activity increases the firing rate and sensitivity of the muscle spindles [RL02].

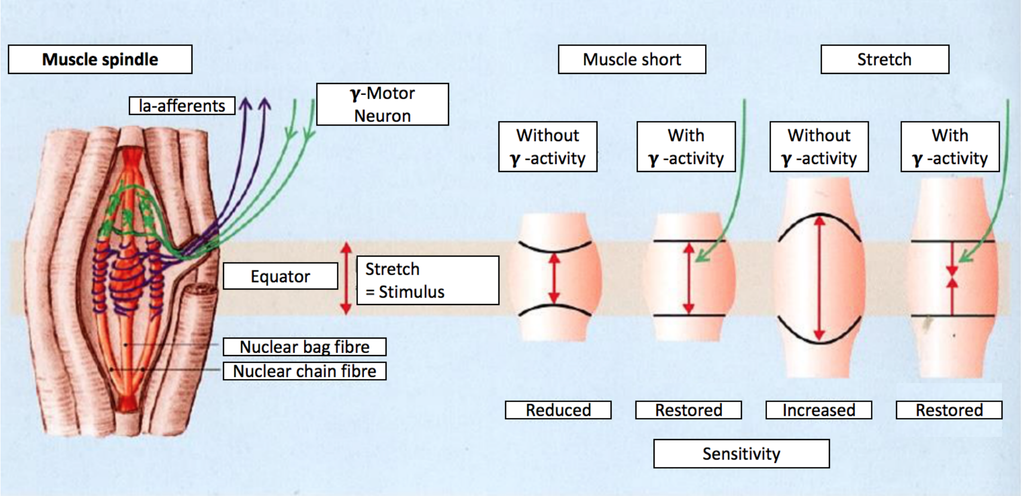

Figure 2.5: Structure and sensitivity of muscle spindles. Figure adapted by [Lau09].

The gamma-activity is possibly influenced by peripheral receptors and descending commands from supra spinal areas. Thus, skin, joint and muscle receptors from the periphery would act together with these same commands on the sensitivity of the muscle spindles and consequently on the length stabilization of the muscle [RL02]. For this reason, Riemann and Lephart [RL02] compare gamma-activity with a „neuronal integration site“.

The mechanoreceptors of proprioception also include the *Golgi tendon organs*. These are connected in series with the working muscles and are located at the transition between muscle and tendon [Lau09]. They are therefore able to perceive changes in tension and strength of a muscle [SCBD04]. Golgi tendon organs react primarily during active muscle contraction and secondarily during passive stretching of the muscle [Lau09, RL02]. If muscle tension is too high, the Ib fibres inhibit the agonist and promote the antagonist [SCBD04].

Each receptor perceives stimuli from a limited tissue area, the so-called receptive field. The receptive field resembles the area from which a sensory neuron can be excited or inhibited [Bir10]. This area corresponds to the anatomical extension of all endings of a fibre, whereby one fibre controls a different number of receptors [Zim19]. For example, one fibre innervates 30 Root hair plexus, but only two to ten Meissner's corpuscles [ibid.]. This finding explains the difference in the size of receptive fields. The smaller a receptive field, the fewer receptors are innervated by a fibre and the better the spatial resolution. However, the spatial resolving power is rather determined by the density of innervation of mechanoreceptor. The innervation density is defined as the number of afferent fibres per $cm^2$ of skin surface [ibid.]. For this reason people have a very good sense of touch on the fingertips compared to the back [Gol14].

The vestibular and visual system processes information about head movement and orientation [GS17]. But since the measurements in this study will be executed with eyes closed, I will not explain both systems more detailed.

Table 2.1: *Summary of mechanoreceptors. Table adapted from [Lau09].*

| Morphology | Fibre type | Adequate stimulus | Adaption | Function |
|---|---|---|---|---|
| Merkel cell | A$\beta$ | Skin deformation | SA | Pressure |
| Ruffini corpuscle | A$\beta$ | Skin deformation | SA | Pressure, gravity |
| Meissner's corpuscle | A$\beta$ | Vibration | FA | Vibration, touch (a.o.) |
| Root hair plexus | A$\beta$ | Vibration, hair movement | FA | Movement, touch |
| Pacinian corpuscle | A$\beta$ | Vibration | FA | Vibration |
| Muscle spindle | la | Muscle elongation | - | Muscle length stabilization |
| Golgi tendon organ | lb | Muscle tension | - | Overload protection |

### 2.1.2 Conversion of Stimuli and Excitation and Nerve Conduction

As I already mentioned in subsection 2.1.1, the adequate stimulus causes excitation of the sensory organ, which is then transmitted to the CNS. This process is explained in detail in the current subsection.

The adequate stimulus triggers ion movements at the membrane of a sensory receptor. As a result, depolarisation of the membrane potential occurs [Lau09]. Thereupon the membrane potential becomes the receptor potential. The speed of excitation conduction depends both on the thickness of the nerve fibres and the degree of myelination [GS17]. The A$\beta$ fibres (e.g. mechanoreceptors) are myelinated, so that the conduction velocity is 30-120 m/s [Lau09]. In contrast, C-fibres (slow nociceptors) are non-myelinated, so

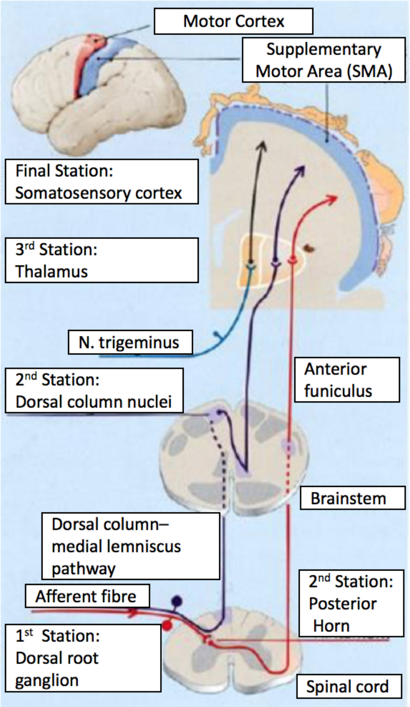

Figure 2.6: Path of anterior funiculus and dorsal Column to primary somatosensory cortex. Figure adapted by [Lau09].

that the line speed is < 1 m/s ([Lau09]). The thickness of the nerve fibres is divided into greek letters, with $\alpha$ describing the largest diameter and $\sigma$ the smallest diameter [ibid.]. The larger the diameter, the higher the conduction velocity.

The action potentials described above are transported via afferent pathways to the brain, where the information is subsequently processed. The afferent nerve fibres of the surface sensor system (A$\beta$) and the depth sensor system (Ia-. Ib- and II-fibres) enter the ascending rear strand path at spinal cord level within the spinal canal [Gol14], as seen in figure 2.6. In the brain stem, more precisely the medulla oblongata (extended spinal cord), the first switching of action potentials to the second neuron takes place, as well as the change of afferent sides from ipsilateral to contralateral [Lau09]. The second and last switch to a third neuron takes place in the thalamus [ibid.]. From there action potentials are directed to the primary somatosensory cortex [Gol14]. At this point afferent nerve fibres in parts of the somatosensory cortex are displayed in a somatotopic arrangement [Ill08]. Somatotopy describes the topographically arrangement of body parts in the cortex, represented by the homunculus [Ill08, Gol14]. The homunculus illustrates that adjacent skin areas project onto adjacent cortex areas and that some areas of the skin are represented in a disproportionately large area of the cortex [Gol14]. A figure of the homunculus can be found in the appendix (fig. A.3).

### 2.1.3 Motor Control

Motor control describes our ability to move and how this is made possible through the control of skeletal muscles by our CNS. In the previous subsections, I described how the various sensors and the processing of stimuli are perceived. Now follows the response to the stimuli in the form of a motor response, since postural control generates specific motor responses to prevent fall. In the following section I will introduce the basics of the interaction and the functioning of motor systems.

After afferent information from the periphery went upwards through the sensors in CNS, the switch in CNS is made to efferent pathways leading to the effectors and their movement execution [HG06]. A special function of our motor system is the spinal motor function, a coordination of movement at the level of the spinal cord, which is a response to a stimulus - the *reflex* [ibid.] A reflex is an involuntary response of the body's effectors (e.g. a muscle) to an excitation of receptors (e.g. by stretching), which means that we cannot intentionally influence this movement [ibid.]. Reflexes are always mediated via the CNS [ibid.]. The anatomical basis of reflexes are the reflex arcs, which have an afferent part of the arch in the form of the sensitive neuron located in the dorsal ganglia and an efferent part of the arch in the form of the motor neuron located in the anterior or lateral horn of the spinal cord [ibid.]. This means that the reflex is only connected in the spinal cord and runs independently of the brain [ibid.] However, the reflex can be influenced by efferent pathways from the brain [ibid.]. There are many reflex arcs in the spinal cord, the best known are the *mono synaptic reflexes* and *multi synaptic reflexes* [ibid.].

The mono synaptic reflexes include the *muscle extension reflex*, which manifests the function of the muscle spindle via the so-called mono synaptic pathway [HG06]. Here, an afferent information of the muscle spindle passes through a nerve fibre of type Ia into the dorsal root of the spinal cord (blue line in fig. 2.7) as soon as the muscle, and thus also the muscle spindle, is stretched [ibid.]. In the spinal cord the information ends at an alpha-motor neuron of the stretched muscle which directly activates the information for contraction of the same (homonymous) muscle [ibid.] At the same time, the antagonistic muscle is inhibited so that it does not contract when stretched [ibid.] (subsection 2.1.1). This inhibition takes place through an interneuron called *Renshaw cell*, which is connected to the alpha-motor neuron through afferents. This results in a rapid contraction of the stretched muscle and at the same time relaxation of the antagonist muscle, also called reciprocal innervation (fig. 2.7) [ibid.].

Besides involuntary activity, the muscle spindle also plays an important role in voluntary motor activity. This process is called co-activation of the motor alpha- and gamma-neurons [HG06]. As soon as information from the brain reaches the alpha-motor neuron, the gamma-motor neurons are simultaneously stimulated, which actively stimulates the muscle spindle [ibid.] Thus, the extrafusal skeletal muscle fibres are activated at the same time as the intrafusal muscle fibres of the muscle spindle [ibid.]. In this way, the muscle spindle works under optimal conditions and does not have to rest. This mech-

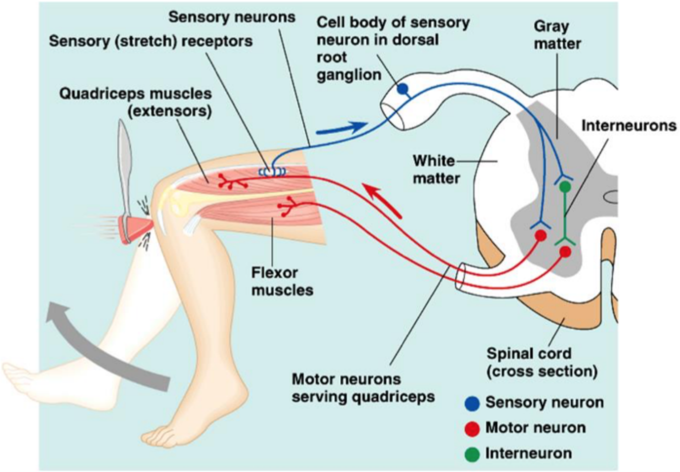

Figure 2.7: The pathway of reciprocal inhibition [Ger16].

anism seems to be responsible for stabilizing the body position during various motor activities [ibid.].

Individual regions and parts of the CNS fulfil different tasks in motor control. Summarized the *brain stem* is the coordinating body of motor control [vdB11]. Reflexes of the brain stem enable the body to adapt quickly to changing external conditions [ibid.]. Among the most important reflexes of the brain stem are *static reflexes*, which control the posture in space [ibid.]. *Statokinetic reflexes* are reflexes that are triggered by movement and ensure that equilibrium is maintained [ibid.].
The *cerebellum* regulates fine motor skills and the *Basal Ganglia* adjust the speed and degree of movement, [ibid.].
The cerebral cortex consists of different fields, whereby primary motor cortex (area 4) and premotor cortex (area 6) form the motor cortex (fig.A.4) [BCP18]. The motor cortex represents the superordinate level of the *pyramid tracts* [ibid.]. The information leaves the motor cortex via the pyramid tracts [ibid.]. Most of the tracts run directly to the motor neurons of the spinal cord [ibid.].

## 2.2 Postural Control

After having introduced the general mechanisms of the sensorimotor system, in this section I will deal with the functions contributing to upright stance and maintaining equilibrium.

The human body is not perfectly aligned with the gravitational axis, it needs a mechanism to maintain an upright position [RBL$^+$17]. In addition, acceleration forces, caused by gravity and external forces, cause the body to sway even when an individual tries to remain calm [SCBD04]. This is done by the postural control system, whose task it is to keep the centre of gravity (COG) above the supporting surface in case of sudden deflection [DHN88]. Even if it is not yet completely known how the coordination of equilibrium is perceived, it is known that several neuronal networks of the CNS contribute to coordination [JH07, DBZO08]. However, we know that areas of the spinal cord, cerebellum, basal ganglia, cerebral cortex and brain stem are important for balance and that it is a holistic, complex sensorimotor and perceptive interaction between our environment and ourselves [JH07, DBZO08, MH10].

In the following subsection I will first introduce the position the parameters that are measured and calculated to analyse human balance are shown followed by the two mechanisms involved in maintaining an upright posture. Then I will explain the sensory systems presented in section 2.1 and their contribution of multisensory integration to postural control and turn to the influence fo cutaneous mechanoreceptors for the human upright stance.

### 2.2.1 COM and COP

The centre of pressure (COP) is the measured parameter in my thesis during the quiet upright stance. To understand the difference between parameters investigated while standing, I will show in this section.
The centre of mass COM is the point where all partial body masses are united. This has the peculiarity that in humans, while they are in bipedal position, the COM is always inside the body. In the upright posture the COM lies 1/3 on the way between hip joint centre to shoulder joint centre [Per10]. This can change slightly depending on the body stature. Referring to research of gait and posture, the term COG is used as the vertical projection of the COM on the ground [Win95] but you find COM and COG as synonyms as well. In physics the COG „is the point at which the total body mass can be assumed to be concentrated without altering the body's translational inertia properties. Forces applied through the COG of an unrestrained body generate zero moment and result in translation but no rotation of the body“ [BRK94]. To measure COG of the human body, horizontal coordinates of each segment are required, which is only possible with motion imaging systems [WPF$^+$96]. The centre of pressure (COP) is the point of application of the ground reaction force (GRF) vector and represents the sum of all forces acting between a physical object and its supporting surface [GH04, FGHL82]. It is identified as an XY plane spatial coordinate [MJFP$^+$15]. COM and COP are related parameters in terms of measuring balance while the COM is subject to change basis on posture and the COP in postural sway [BRK94]. In other words the COP spatial position changes according to the displacement of the body's COM [MJFP$^+$15]. The magnitude really indicating body displacement is COM positioning variation while the COP is an expression of the neuromuscular response to COM displacement [ibid.].
Postural sway movements are divided in anterior-posteroir (AP) direction (forward and backward) or y-direction and the medial-lateral (ML) direction (side-to-side) as x-direction. These movements can be detected by force plate sensors and calculated as the COP. It is

quiet independent of the COM [WPF+96]. During quiet standing COP shift profiles are closely related to the sway of COM [MSC99]. Force plates are considered to be the gold standard in terms of measuring balance and postural sway [CBP+10], while scales and specific clinical tests are alternatives [BWDWM92].

### 2.2.2 Rambling and Trembling

The term *rambling and trembling* was developed of decomposing stabilograms into two components [ZD99]. Rambling „reveals the motion of a moving reference point with respect so which the body's equilibrium is instantly maintained. The trembling component reflects body oscillation [of COP] around the reference point trajectory" [ZD99] as seen in figure 2.8 lower plot. Rambling and trembling is based on the concept of instant equilibrium point (IEP) the so called zero-force point [ibid.]. When the resultant of all forces acting on a given body is zero its condition is in equilibrium [ZD02]. If the sum of the external moments acting on the body is zero, the body does not move in the vertical direction [ZD99]. The sufficient and necessary condition for equilibrium is $\sum F_{hor}=0$, where $F_{hor}$ are external forces acting on the body in horizontal direction [ibid.]. When the body is at equilibrium ($F_{hor}=0$) it is either at rest or its COM moves with a constant velocity [ibid.]. The position by which the equilibrium is maintained is called reference position, as seen in figure 2.8 upper plot when $F_h$ crosses zero-line [ibid.]. The IEP is defined as a COP position in an absolute system of coordinates at an instant when $\sum F_{hor}=0$ [ibid.]. During this moment the body is instantly in a reference position [ibid.]. The discrete IEP trajectory is the result of consecutive positions of the IEP and represents discrete observations of the reference point trajectory [ibid.]. The continuous IEP trajectory obtained by a cubic spline interpolation of the discrete IEP trajectory manifests the rambling trajectory [ibid.].

### 2.2.3 Control Systems

The terms used to describe the balance of the body are not unique. Balance, postural control and maintaining equilibrium are used synonymously [THC+06]. It is important to distinguish postural control during gait from that during standing upright in quiet manner, as the control mechanisms have different degrees of influence [Win95]. This is due to the fact that during walking a much larger proportion of voluntary movements are performed. However, a clear line between the control mechanisms cannot be drawn, since both mechanisms act along when standing quiet and when walking [RL02].
Postural control can be divided into two different but interacting systems:

- anticipatory postural adjustments or *feedforward control*, in which postural corrections are carried out before a movement

- reactive system or *feedback control*, in which the corrections are made in response to disturbances [GS17].

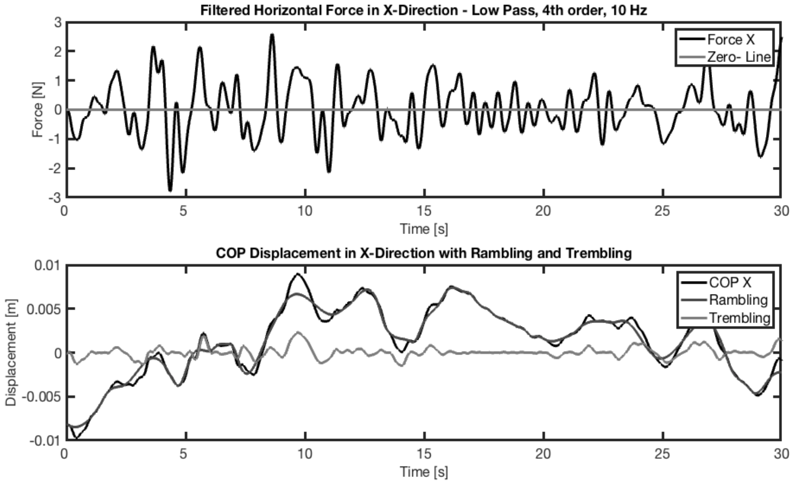

Figure 2.8: Time-series of the horizontal Force ($F_h$, upper plot), instant equilibrium points when $F_h$ crossing zero-line and trajectories of $COP_x$, Rambling, and Trembling components in lower plot for a representative participant.

*Feedforward control*, the first system, is based on experience and learning, anticipatory correlation of sensory and motor systems in anticipation of postural requirements [Coo17]. This feedforward control is already active before the movement is executed. This control includes muscles that are not directly involved in the targeted movement, e.g. the upright position, but are involved in maintaining postural control [GS17]. This can be the muscles of the upper limbs in the example of the upright stand. If it is expected that both balance and stability are needed and the CNS can program a postural alignment before the planned movement begins, this anticipatory control is used [ibid.]. The experience plays an important role, which teaches the CNS to accurately assess the effects of a planned disorder and to use the synergistic, anticipatory activation of specified muscles [SA07]. In this way it is possible to achieve the highest possible degree of body stabilization [ibid.]. The feedforward control is tailored to characteristics of particular movements, such as speed and direction of an expected disturbance [PJ12]. Feedforward control is reduced when a disruption is unpredictable [GS17]. In this case the feedback control, which I explain in the next paragraph, is activated more often [SA09].

*Feedback control*, the second system, is a protective or compensatory reaction. It can also be referred to as compensatory postural adjustment (CPA) [SA09]. It describes reactions by a coordinated activation of muscles to stabilize the body as a result of a disorder [TvAS+09]. These reactions are not reflexes, but rather systematic activations of muscles - thus they are strategies [KSJ+12]. Since CPA are initiated by sensory feedback, they cannot be predicted [AFH+05]. Different muscular patterns are activated by individual protective strategies and provide adequate postural stability [GS17].
In order to restore the balance of the human body, we mainly fall back on three essential categories when standing upright. In two strategies the feet remain in a fixed position.

In the third, the supporting surface is changed by grasping or walking [Hor87, Hor06]. With the first strategy the sway of the human body during stance is balanced by movements of the ankles [HN86, Rot93, Coo17]. This is done by an activation from distal to proximal [ibid.]. With the second strategy the lower trunk, pelvic and hip muscles are activated first [GS17]. This activation is a cranial-caudal (proximal-distal) recruitment [ibid.]. However, it is noticeable that in many situations steps are taken even if the balance is not compromised and the line of gravity runs inside the supporting surface [MM97, Coo17]. The third strategy involves taking a quick step and reaching for something to restore balance [GS17]. These responses are much faster than voluntary limb movements and can effectively slow down the movement of the COM induced by sudden unpredictable disturbances of balance [MM06]. The step is reactive in this situation [GS17]. However, elements of planning and strategy are always present [ibid.]. When we take a step to initiate locomotion, we plan ahead and initiate feedforward strategies [ibid.]. Since in this case cognitive elements come to the fore, it is no longer a protective reaction [ibid.].

Once a disturbance of balance occurs, we are usually able to use different strategies [GS17]. The ability to select the appropriate reactive strategy for postural control involves complex and integrative sensorimotor processes [ibid.]. Efficient postural control in humans requires precise knowledge of the spatial configuration of the entire body (body schema) and the localization of the body's COG relative to the line of gravity and support surface [Jun82]. Because of this the use of strategies is very dependent on situations [GS17]. The order of muscle activation varies in relation to needs and possibilities. The choice of a strategy depends on getting used to previous experiences, fears and expectations [Tin07]. The sequence of muscle activation from distal to proximal across several joints can be modified little in space and time [DHN88]. This suggests that sensory afferents trigger centrally pre-programmed response patterns (muscle synergies) and the reactive, automatic, postural corrective movements of the feedback control probably take place via poly synaptic, spinal reflexes in centrally pre-existing muscle activation patterns [DBH88]. The response also varies depending on the feet, whether they have freedom of movement or are kept still at the time of displacement, whether the support area is smaller or larger than the feet, how the displacement occurs, and whether participants in the study are instructed to stand still or allowed to move [GS17].

As I already mentioned at the beginning of this section, the activation of feedforward and feedback control cannot be completely separated from each other. Thus there is an interaction during postural control [SKA10]. The central organization of postural control summarized in a schematic diagram can be seen in figure 2.9.

### 2.2.4 Multisensory Integration for Postural Control

At first the CNS has to perceive the current state of the body to its environment in order to generate a contextual postural activation [GS17]. This is done by multiple sensory

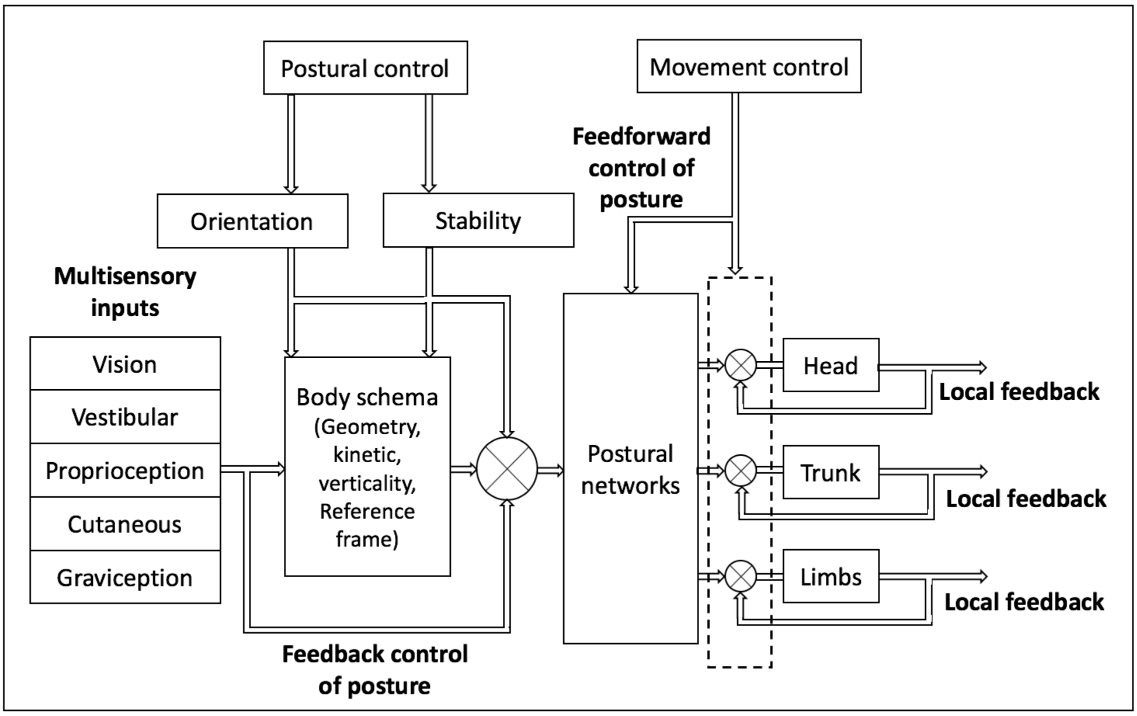

Figure 2.9: Central organization of postural control summarized in a schematic diagram. Figure adapted by [Mas94].

references of the human body: gravity (vestibular system), proprioceptive signals for body positioning, contact with the environment (somatosensory systems) and the relationship between body and objects in the environment (vision) [MMP05, HHSC97]. The response of healthy humans to sensory information is appropriate motor response (subsection 2.1.3) to ensure both anticipatory and reactive aspects of postural control [GS17]. The rebalancing of multi-sensory processes is of high importance, since the balance of the human body must be adaptable in different situations [ibid.]. This rebalancing of sensory information is an ability of the CNS to suppress erroneous or weak information and at the same time become more sensitive to other sensory information [PBC$^+$12]. As environmental conditions or the state of the nervous system change, visual, vestibular and somatosensory information is dynamically rebalanced [LKJ14]. The CNS selects the category of sensory information it considers most important in a given situation and ignores information that is considered less reliable [GS17]. Sources with variable input are more likely to be ignored [Bro04]. This phenomenon is called sensory reweighting [NB78].

The previous research on postural control is considered to be well researched and recognized to date. Nevertheless, new approaches are discovered that lead to plausible explanations. This includes the sensory system of somatic graviception for postural control. Several studies have proven the existence of this system, which is an example for the complexity of postural control and its multisensory integration. The somatic graviception is a system placed in internal organs [Mit96, MIT92, VMS$^+$02, TaBN$^+$04, CDM14]. Graviceptors are specialized sensory receptors that detect weight shifts in relation to gravity [GS17], such as the weight of shifting fluids in the intestines [Mit96]. This information helps to internally map the vertical axis of the human body [KD05, Mit96].

### 2.2.5 The Influence of Cutaneous Mechanoreceptors

In this section I present the contribution of cutaneous mechanoreceptors to the human upright stance. They play a special role, because they are always in contact with the physical environment, except during a jump.
First the CNS must determine the current status of the body in relation to its environment in order to generate a context-dependent postural activation. This is done, as I have shown in the last subsection 2.2.4, with the multiple sensory references of gravity (vestibular system), contact with the environment (somatosensory systems), proprioceptive signals for body positioning [MMP03], and the relationship between the body and objects in the environment (vision) [HHSC97]. The integration of all three systems enables the balance to be maintained in an upright position [METD04]. The postural control of the human being must be adaptable and stable in many different situations involving a process of rebalancing multisensory stimuli [MMP03].
With regard to the upright position, the proprioceptors of the cervical spine, sacroiliac joint and feet are particularly important for the sensorimotor system [Lau09]. Together with the vestibular system the proprioception of the neck is essential for the retaining and positioning reflexes [ibid.] With help of visual information motor programs and reflexes take place, which guarantee posture, position and balance [GS17]. Mechanoreceptors provide not only the detection of objects but also decisive information for postural control [GS17]. Thus, the cutaneous mechanoreceptors in the feet are important for the control of balance when standing [ibid.]. The plantar mechanoreceptors and their contribution to postural control are extensively studied [SSM09, SMSO09, SGM17], since they are the only points of contact with the ground when standing upright without additional support.
If the stance position is changed, the pressure areas of the foot soles also undergo a change [GS17]. The receptors provide the CNS with reliable and important information about the direction and amplitude of movement in the centre of the pressure area, the position of the feet and the degree of stress [ibid.]. When standing, the sole of the foot is loaded so, that plantar cutaneous mechanoreceptors perceive the local pressure distribution and report indirect information about the movement of the body in relation to the support area and stability limits [JROL98]. Both rapidly and slowly adapting cutaneous mechanoreceptors are very sensitive to the forces acting on the soles of the feet [ibid.].
In order to illustrate the importance of plantar cutaneous mechanoreceptors for postural control, several studies have been conducted to influence tactile afferent information [SSM09, SMSO09, SGM17, KHGZ09]. Postural control was negatively influenced by de-

sensitization of cooling and stopping the blood flow (anaesthesia) of the mechanoreceptors and by changing the properties of the supporting surface [ibid.]. The results of these studies support the hypothesis that plantar cutaneous afferents contribute to the control of balance. A continuous rebalancing of different categories of sensory information is necessary for an efficient, flexible and context-dependent postural control [CEVD13]. The CNS selects the category of sensory information that it considers most important in a given situation and ignores information that is considered less reliable. Sources with variable input are more likely to be ignored [dLPPC+12]. With these findings, the importance of cutaneous mechanoreceptors becomes clear, since healthy individuals rely 70% on somatosensory information in a well lighted and bright environment with a stable support surface to maintain an upright standing position [Pet02]. Visual (10%) and vestibular (20%) information has a much lower proportion [ibid.]. However, sensory weighting shifts from somatosensory to vestibular cues when an individual is no longer standing on a stable but also on a fluctuating surface [ibid.]. Increased perception via the visual system is also confirmed, although the somatosensory and vestibular systems are not directly affected [BPB+12]. However, these are patients with Parkinson's Disease or stroke who have neurological disorders [YKB+06, BGL+06]. The importance of the cutaneous mechanoreceptors and thus also the high percentage (70%) of sensory information for maintaining an upright posture is demonstrated by patients with partial or complete sensory deficits whose movements are imprecise and uncontrolled [BTF+99, SPC+06]. Patients with a complete sensory loss within the major fibrous structures and without cutaneous sensations or proprioception are imprecise and asymmetric [LCC95, FL95]. This state even persists when visual information is available [BTF+99].

The mechanoreceptors found in the skin are located evenly in deeper tissue layers and thus contribute to proprioception (subsection 2.1.1) [Lau09]. However, the receptors in the skin also transmit information about the joint position to the CNS [CRTG05]. Via non-muscular afferents they provide information on the position and movement of joints [CHK+11]. Thus, the receptors in the skin reliably fire nerve signals depending on the position of nearby joints [AHRRC07].

## 2.3 The Human Forearm and Wrist

This last section of background research provides information about the human forearm and its transition to the wrist since I deal with providing cutaneous stimuli on the forearm in my thesis.

The forearm consists of two bones, the radius and ulna. Both bones are connected by a ligament (Ligamentum anulare radii) and a membrane (Membrana interossea antebrachii) [Fal08]. The muscles are divided into two groups according to their position. The muscles on the inside of the hanging arm are flexors, which bend the arm, hand and fingers. The muscles on the outside, the extensors, stretch the arm, hand and fingers [dMH94]. The extensors are subdivided into two separate layers that extend from the

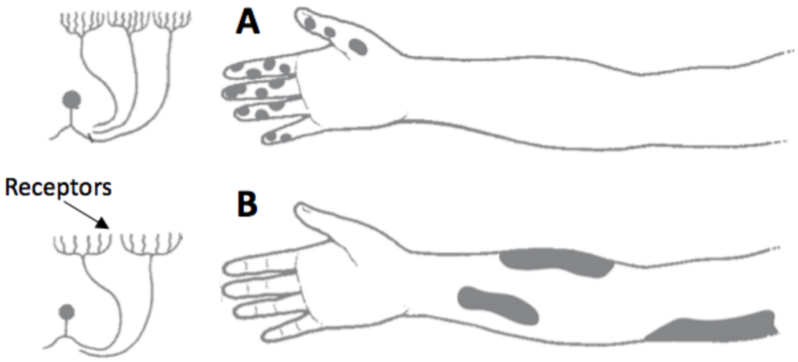

Figure 2.10: (A) the size of receptive fields and the sensor size on the finger and (B) receptor size and size of receptive fields on the forearm. Figure adapted from [KSJ+12]

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surface of the body into the depths [Fal08]. In the area of transition to the wrist, the muscles of the upper layer merge into tendons that extend to the fingertips [ibid.]. The muscles of the deeper layer change into sight directly at the wrist. Thus the area around the wrist has only a small amount of soft tissue. In addition, the proportion of subcutaneous fat on the hands and lower arm is generally low [dMH94].

The innervation of the skin can be divided into different areas, so-called dermatomes [PKS14]. A dermatome is innervated by certain afferents (subsection 2.1.2) of a segmental arrangement of the spinal cord [ibid.] The skin areas of the index finger, thumb and the area described above under which the extensors lie form the dermatome C6 [ibid.]. The central extensions of the mechanoreceptors and proprioceptors from the skin (A$\alpha$ and A$\beta$ fibres) are interconnected in the same segment [ibid.] This segmental synaptic interconnection of the mechanoreceptive and proprioceptive afferents serves, among other things, to control spinal reflexes (see subsection 2.1.3) [ibid.]. Afferents of different modes, even mechanoreceptor and nociceptor inputs, can converge on common multimodal neurons [ibid.]. An illustration of different dermatomes which are of importance in the sensation of touch can be found in the appendix (fig. A.2).

The somatosensory significance of the forearm is relatively low. The size of the receptive fields is relatively big, so that the two-point threshold is about 15 mm, as seen in figure 2.10 [SS06]. This is also reflected in the size of the representative area in the somatosensory cortex [PKS14]. Areas with a high receptor density, such as the hand or the lips, are significantly larger than that of the forearm [ibid.] (fig. A.3).

There are small differences between the receptors at the fingertip and on the forearm. The receptors in the hairy skin show no effect on temperature dependency compared to those in glabrous skin [VB86]. Additionally the skin of the fingertips is thicker because of the cornea (Callus) (fig. 2.3). As a result, a lower mechanical stimulus is necessary to activate the Meissner's corpuscles and Merkel cells [VB86]. However, this difference in threshold is compensated by the increased number of receptors in the fingertip and their smaller receptive fields (see subsection 2.1.1) [ibid.].

# Chapter 3

# State of the Art

The contribution of cutaneous mechanoreceptors to proprioception has become an important area of research since it has been known that they are found in other tissue layers besides the skin. A large number of research papers have been published, particularly in relation to postural equilibrium and postural control. Many investigations of human postural control have removed inputs from feet and ankle to study the influence of visual and vestibular inputs to see proprioception's contribution while standing free without additional support [Nas81]. In combination with these proprioceptive inputs somatosensory stimulation from contact of the feet with the support surface has been shown to play an important role in maintaining upright stance [DDGM84, JR94]. Only because of the groundbreaking study by Jeka and Lackner [JL95] it became widely known that haptic stimulation by fingertips also has an influence on postural stabilization. There are several studies that investigate different influences such as induced sway, interpersonal contact, different contact points and earth fixed contact points through light touch on postural sway.

A study, which is connected to light touch by a mobile, not earth-fixed contact point that provides active haptic stimuli on the forearm, is not available due to an extensive literature research to my best conscience. For this reason the state of the art on light touch and its effect on postural sway is worked out in the following. Additionally I summarize my findings of internally and externally factors effecting the mechanisms of human postural control.

## 3.1 Light Touch

The terms *light touch cue* and *haptic cue* were invented by Jeka and Lackner [JL95] in 1995. The sense of haptic cue is the cutaneous and kinaesthetic sensory information form mechanoreceptors in the skin, muscles, joints and ligaments of the hands and fingers during touching or manipulating an object [Mat88]. Trendsetting was the important role of additional haptic information for the control of the upright position, which is provided by lightly touching a stable support surface with the tip of the index finger, as seen

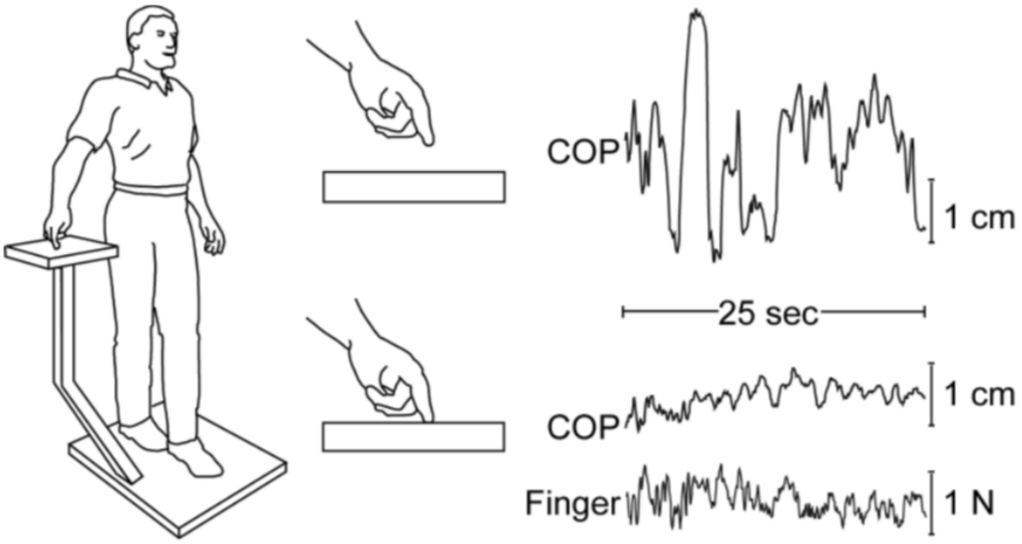

Figure 3.1: **Left:** Experimental setup used to investigate the influence of light touch of the finger on posture. **Right, top:** Without finger contact in darkness, there is substantial sway of the centre of pressure (COP). **Right, bottom:** Fingertip contact at <1 N attenuates sway. Surreptitiously, oscillating the touch surface entrains posture (not shown). Figure from [Nel02].

in figure 3.1 (left). [HVL94, JL95]. A light touch cue is somatosensory information of the finger tip by touching an object with a contact force less than 1 N (100 g) [BPSPP11].

Compared to a control condition in which the arms are passively suspended beside the body, postural sway is reduced by more than 60% when the standing subject touches a solid surface with the index finger with a force of 5-8 N [Hol87, HVL94, JR94]. This reduction of the postural sway is due, among other things, to a physical stabilization that the body experiences through the contact [ibid.]. A reduction of postural sway of more than 60% was also observed when the subject made contact with the solid surface through a light touch (<1 N) [ibid.]. With such a weak contact, both active and passive dynamic support can be ruled out, which is why the postural sway must have decreased through the perception and processing of haptic information [HVL94]. The maximum sway reduction attributable to actively applied contact forces is only 2.3% [JL95]. Indicating that biomechanical factors are playing a significant role, in conditions involving five to eight N of applied contact force, attenuation of sway through dynamic and passive stability is estimated to be 20 - 40% [HVL94]. The physical analysis indicates, that sway reduction was achieved through different means, even though the amount of sway was equivalent with small and large fingertip contact forces [JL95]. Five subjects (1 f and 4 m) from age 20 to 50 years confirmed to be healthy and physically active with no known musculoskeletal injuries or neurological disorders participated [JR94]. The individuals stood with left foot in front in tandem Romberg stance and head as well as eyes straight ahead [ibid.]. Six experimental trials included three fingertip contact conditions (no contact, during which the subject's arms hung passively, touch contact, in which the subject was limited to 0.98 N of applied horizontal or vertical force on the touch apparatus, and force contact, during which the alarm was turned off and subjects could apply as much force as desired)) and two visual conditions (vision, eyes open, and dark, eyes closed) [ibid.]. In relevant trials an auditory tone appeared when an adjustable threshold force greater than 0.98 N was reached (fig. 3.1) [ibid.].

Between force contact (5 - 8 N) at the fingertip and the body sway is a time lag by approximately 80 ms, whereas the light touch contact conditions (1 N) show a greater time lag between medial ML sway and force at the fingertip wit about 300 ms [JR94]. The force contact conditions (vision force and dark force) have a nearly in-phase relationship between body sway and fingertip contact [ibid.]. This relationship implies contact forces are used to offset physically movements of the body's COM during force contact conditions [ibid.]. Compared to this the light touch cue provides information about the position [ibid.]. A decrease in horizontal fingertip force indicates sway to the left while an increase in horizontal fingertip force indicates rightward body sway ([ibid.]. In Jeka's and Lackner's work [JR94] they were partly aware of the relationship between fingertip force and body sway as they let up on their finger as they swayed in one direction to not set off the alarm [ibid.].

In addition to the fingertip light touch cue, the position of the arm and finger joints also plays a role in Jeka's and Lackner's experiment, because one arm does not hang passively beside the body. Interrelating muscle afferents and other proprioceptive activity receive information from ongoing arm configuration to convert them into motor commands [BWCS82, Mat81, Mat88]. Muscle spindle signals from the arm and hand are processed in area 3a of the primary somatosensory cortex (fig. A.3 in the appendix) and projected directly to topographically related parts of area 4, to parietal cortex and the primary motor cortex [JR94]. Active and passive joint displacement get processed in area 5 of parietal cortex (fig. A.4 in the appendix) [Phi85].

Cutaneous mechanoreceptors provide information about joint movement and position (subsection 2.1.1 and 2.2.5) that finger joint movement can provide information about body sway [JR94]. Besides that, slowly adapting (Merkel cell, Ruffini corpuscle) cutaneous mechanoreceptors of the index finger pad are primarily responsible for tactile form and roughness perception through distribution of forces across the skin [JH92, JR94]. Vertical or shear forces through light touch contact may provide comparable information about body sway through slowly adapting receptors [JR94]. This statement is supported by the measured detection thresholds for movements of a polished glass plate across the finger pads [SWL90]. More than 90% of direction of motion was identified accurately with a contact force of approximately 0.2 N [ibid.], which is much less than the maximum force of light touch (1 N). In Jeka's and Lackner's [JR94] experiment it is remarkable that all subjects made a contact of 0.4 N with the fingertip, even though they were allowed up to 1 N of force. This value is in consistent with the maximal afferent activity observed at approximately 0.3-0.5 N [WJ87].

Fingertip contact forces are not enough to counteract COM [HVL94]. Therefore a muscle activity is necessary to attenuate postural sway. The relationship between electromyography and postural sway is notable, since electromyography (EMG) activity occurs within 100 ms in response to perturbations of a standing subject's base of support [Nas76]. But actual compensatory changes in sway can take 300 ms and longer to appear [ibid.]. The lateral fingertip contact force of light touch begins 150 ms ahead of changes in ML sway of the COP, in turn, EMG activity of the left leg begins 150 ms ahead of changes in ML COP sway [JL95]. Since the time course is divided into two stages of equal duration, we can assume that the EMG response is a supra spinal long-loop pathway [DH86]. Since the subjects can predict the periodic nature of body sway, it can also be a conscious anticipatory innervation [JL95]. Medial-lateral COP sway and fingertip forces maintained a similar temporal relationship with EMG activity of the right leg [ibid.]. During force contact fingertip contact force changes followed by EMG activity [ibid.]. This suggests that the contract forces are more closely synchronized with the ML COP sway and do not pre-cue the leg muscle activity [ibid.]. With physical support, the contact forces at the fingertip increase as the subjects swing towards the touch stick and decrease as the subjects swing away because the contact forces are covariant with the ML COP sway over such a short duration (70 ms) [ibid.]. During light touch conditions the EMG activity in postural leg muscles increases approximately the double versus force contact of the index finger [ibid.]. With force contact, minor body sway oscillations are damped by a kind of braking function using small muscle contractions [ibid.].

Jeka and Lackner [JL95] differentiate COP and body sway. The COP is as I describe in section 2.2.1 the point of application of the ground reaction force vector and represents the sum of all forces acting between a physical object and its supporting surface [GH04, FGHL82]. The body sway is the movement of the COM (section 2.2.1) and is measured by an light-emitting diode (LED) at the subjects hip and an camera system [JL95]. COP and body sway show the same reaction to light touch and force contact [ibid.].

### 3.1.1 Light Touch Through Additional Device

Under certain circumstances it is even possible that a light touch contact can achieve the same reduction of COP displacement like a physical support. Jeka and Lackner [JEBL96] examined five subjects (4 male, 1 female) between 20 and 40 years and additionally five congenitally blind (unable to see or with severe visual impairment since birth) subjects. This time, the participants in the study did not have contact only with the tip of the index finger, but held a cane made of aluminium, with a handle formed grip in their hand [ibid.] The feet were in Romberg tandem stance and the test was performed with eyes closed and eyes open [ibid.]. In the experimental trials the cane was held in two different positions, one perpendicular to the ground and one slanted, the cane tilted toward the

subject's right side at approximately a 70° angle relative to the metal bar [ibid.]. The metal bar on which the cane tip rested was bolted 35 cm and 55 cm to the right of the subject to insure the required perpendicular and slanted cane angles, respectively [ibid.]. Cane length was increased in the slanted conditions so that it was held at approximately the same elevation and elbow angle as in the perpendicular conditions [ibid.] During light touch contact the subjects were limited by an audio tone to a maximum of 2 N in vertical and horizontal direction while force contact was unrestricted [ibid.]. In contrast to the work of light touch at the fingertip (<1 N) [JR94], was measured at the contact point of the cane and force plate due to the handle of the cane [JEBL96].
When the cane was held in a vertical position with light touch, the ML COP displacement was reduced by about 20% compared to the control condition in which the subjects stood with passively hanging arms [JEBL96]. The COP displacement even decreased by 50% and more when the cane was held at an angle [ibid.]. Light touch contact with an inclined cane had an even greater effect than physical support with a vertical cane [ibid.]. This indicates, if haptic cues are functionally meaningful for the task, sensory information can be as effective as physical support in stabilizing upright stance [ibid.].
Since both congenitally blind subjects and sighted subjects who were blindfolded show the same effect, the statement that this is a truly haptic process is supported [JEBL96]. People who are blind from birth cannot have haptic postural stabilization within a visually based reference system, which means the visualization of self-orientation with given haptic cues [ibid.].
The result that a cane held at an angle shows a greater reduction of the COP displacement than a cane in a vertical position [JEBL96] coincides with the investigations of Biggs and Srinivasan [BS02]. The latter investigated vertical and tangential displacements and forces on the finger pad and forearm [ibid.]. For the finger pad, the sensitivity threshold for displacement was found to be slightly lower for tangential forces, but the force threshold of tangential was five times higher than for vertical ones [ibid.] Since I can assume that a lower sensitivity threshold at the soles of the feet leads to a better postural control [SSM09, SMSO09], I can make the connection that a lower sensitivity threshold at the finger pad can have a similar effect. For this I have to show the apparatus and measures of Jeka et al. [JEBL96] in more detail. The skin on the cane held next to the body perpendicular to the ground experiences both vertical and shear forces when swaying ML in the direction of the cane. A cane held with an angle of 70° experiences similar forces, but the proportion of vertical forces is probably higher than with the cane held vertically. This is because the force vector in the angled cane is more perpendicular to the contact point than in the cane held at 90°.

### 3.1.2 Light Touch at Different Body Parts

The effect of the light touch at the finger tip on postural sway has been extensively and thoroughly investigated. The positive effect therefore raises the question of whether a light touch also has a reducing effect on postural sway at other parts of the body. There is also the question of whether stability during standing is improved by passive

tactile input related to body sway that does not involve active manual touch. Among others Rogers et al. [RWLF01] addressed these question and examined the light touch cue provided by an earth-fixed reference on top of the right shoulder, on the lateral side of the knee joint and on both [ibid.]. The effect was examined in addition to diabetic patients with peripheral neuropathy, older people (70-79 y) and to eight (4 m and 4 f) healthy young adults (21-37 y) without neurological or musculoskeletal problems [ibid.]. There were two different conditions for the base of support, which was a clear surface or foam. With eyes closed standing on clear surface and the stimulus at the shoulder reduction of sway (28.8±2.0%; p<.0001) was greater than when it was placed on the leg (21.6±2.3%; p<.05) compared to the control condition with eyes closed and without stimulus on clear surface [ibid]. With both shoulder and leg stimuli, the reduction in sway was significantly greater (41.9±2.9%; p<.05) than when only the shoulder or leg stimulus was available even though there was no control condition for this stimulus [ibid.].
To identify any placebo effect of a similar stimulus, trials were undertaken with a 25 g weight (0.25 N) covered with the same fabric resting on the shoulder [RWLF01]. The weight was placed on the shoulder in a manner that did not alert the subjects that this was different to the stationary stimulus [ibid]. Because it was not attached to a rigid support, it did not move relative to the skin as the subject swayed, although through its inertia it could provide a very small tactile input related to sway [ibid]. The resting weights did not have any significant influence on reducing the sway [ibid.].
This means that the tactile stimulus must be related to body sway in order to produce a reducing effect. Since the body is to be viewed as an inverted pendulum with the joint at the ankles, in this experiment the stimulus strength at the shoulder has been shown to be three to four times higher than at the leg [ibid.] Accordingly, the stimulus at the shoulder caused a greater reduction in swinging than at the leg [ibid.].
On the leg and shoulder are the rapidly adapting (FA) cutaneous Pacinian corpuscles and root hair plexus [JH92]. They are very sensitive to vibration, movement between the skin and a contact surface as well as to light touch [ibid.] Even the discharge of a single receptor of the Pacinian corpuscle leads to a perception of touch, which makes them very sensitive [MGB90]. In the study by Rogers et al. the subjects showed a spectrum of body fluctuation of less than 1.5 Hz. This is considerably lower than the typical discharge rates (10-300 Hz) of FA receptors [JH92]. However, it can be assumed that by rubbing the earth fixed reference an almost continuous rubbing over the skin and thus a continuous stimulus was exerted and this probably modulates the high discharge rate of these receptors with the profile of the body sway [RWLF01]. The light touch with the finger tip generates both shear forces if the finger did not slip or a movement of the finger if he slipped [JL95]. Each of the two situations would have produced different cutaneous afferents and this in the study by Rogers et al. also [RWLF01]. This suggests that no single class of cutaneous sensory receptors is responsible for reducing body sway [ibid.]. Jeka and Lackner [JL95] argued that, in addition to the light touch, the position of the arm, hand and finger through joint positions and joint movements are also responsible for the light touch effect. Rogers et al. proved that this contribution is not absolutely necessary. This is consistent with the statement that the CNS preferably uses

sensory impressions from the periphery rather than central control when assessing the movement and position of the limbs [RWLF01].

Rogers et al. have proven that other body points can also decrease the body sway by light touch, but they have not analysed the effect in relation to light touch with the finger tip. Krishnamoorthy et al. [KSL02] have investigated this in their work. They compared the effects of the index finger touch with the head and neck touch [ibid.]. These two regions of the body have different sensory resolution and sensitivities for normal and lateral skin deformations, especially compared to the finger pad [ibid.] The finger provides information about possible deviations of the trunk from the vertical via the kinematic chain, which must be combined from the arm [ibid.]. This information is provided directly by the contact with the head or neck [ibid.]. The assumption that despite the disadvantage of the sensory resolution of the head and neck, a higher effectiveness of sway reduction to be expected was confirmed by the investigation [ibid.]. Eight healthy subjects (4 m, 4 f) at a mean age of $25.1\pm3.7$ y without any known neurological or motor disorder were examined. All touch conditions produced a lower postural sway ($p<.05$) than the no touch condition [ibid.]. It was noticeable that the mean migration area of the COP was smaller under light touch conditions at the head and neck than under finger tip [ibid.]. There was no differences between the effects ($p>.9$) at the head or the neck [ibid.] A difference between finger tip, head or neck was not analysed.

Wasling et al. [WNGO05] have set a study that is very interesting for the analysation of this thesis. To analyse the influence of shear forces and vertical forces, they used an air-stream as a tactile stimulus in addition to an earth-fixed reference point that generates both shear and vertical forces [ibid.]. The stream had a constant temperature of deg30C and an impact set at 0.08 N before each session [ibid.]. The tactile stimuli were applied to the glabrous skin of the tip of the index finger or to the skin of the distal forearm 2 cm proximal of the ulnar styloid process with a maximum of 1 N [ibid.] (fig. 3.2). The test was performed with eight (20-34 years) naive volunteers, four females, and four males [ibid.]. The subjects had no previous experience of the different tasks [ibid.]. The subjects stood in bipedal Romberg's stance with eyes closed on a force plate as control condition [ibid.]. The air-stream reduced the amplitude of sway (COP) at the glabrous skin ($p<.01$) but not at hairy skin [ibid.]. There was no effect on the path-length of the COP [ibid.]. The weak effect on hairy skin reflected the perceptually poor directional sensitivity for the air-stream stimulus (0.08 N) in this cutaneous area [ibid.]. Through light touch contact path-length as well as sway amplitude decreased [ibid.]. At hairy skin respectively $p<.01$, path-length at glabrous skin $p<.05$ and sway amplitude $p<.001$ [ibid.]. This shows that a light touch with <1 N at the distal end of the forearm has a reducing effect on the postural sway.

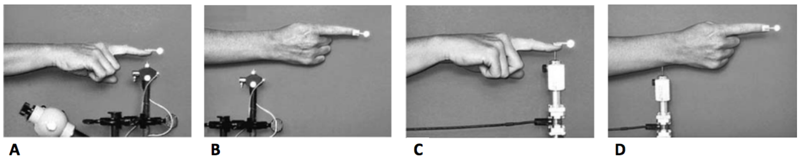

Figure 3.2: The glabrous skin of the right index finger (A, C) and the skin of the distal forearm (B, D) were the receptive surfaces for the air stream (A, B) and the physical (C, D). Figure adapted from [WNGO05].

## 3.2 Postural Sway

The reactions of the human body to fluctuations and which mechanisms it uses has not yet been fully clarified, as there are various models that have not yet been proven in their entirety. The most widely accepted model to date is that of active and passive postural control by Winter et al. [WPP$^+$98]. It turned out that the postural control in a side-by-side stance in AP direction is under total ankle (plantar/dorsiflexor) control and the ML direction under hip (abductor/adductor) control.

Since the science for verifying this theory refers mainly to ankle control, I will explain it in the following for the understanding of the postural sway.

### 3.2.1 Active and Passive Postural Control

To maintain equilibrium in an upright posture we assume that both passive and active components of the human body are active. Stiffness or viscosity, intrinsic mechanical properties of the tissue, serve as passive torques of the postural control mechanisms that occur without time delay [LL02]. In contrast, active torques resulting from active muscle contractions are generated [HBP06]. However, this mechanism is accompanied by a time delay due to sensory transduction, transmission, processing and muscle activation [MLR$^+$08].
By applying a stiffness control strategy, Winter et al. [WPRI01, WPIG03, WPP$^+$98] have developed a control model for the upright stance, assuming that the human body behaves like a pendulum with the ankles as its joint. The ankle torque is proportional to the angle of the pendulum from the vertical of the body [ibid.] Especially interesting of this model is that the COP behaves in phase with the COM during the sway of the human body (fig. 3.3, section 2.2.1) [ibid.]. The controlled variable COM is related to the control variable COP by the human pendulum [GTKH99]. To remain in a position centrally between the feet, the COP follows the COM [WPP$^+$98]. Theoretically, the COP at low oscillation frequencies below 1 Hz is completely consistent with the COM [Win95]. For particularly pronounced compensation movements of the pendulum, the displacement of the COP exceeds that of the COM [ibid.] Comparable results of the relationship between COM and COP have been published by Lafond et al. [LDP04]. The basic interaction between COP and COM migrations during upright stance is illustrated by fig. 3.4. The GRF as a

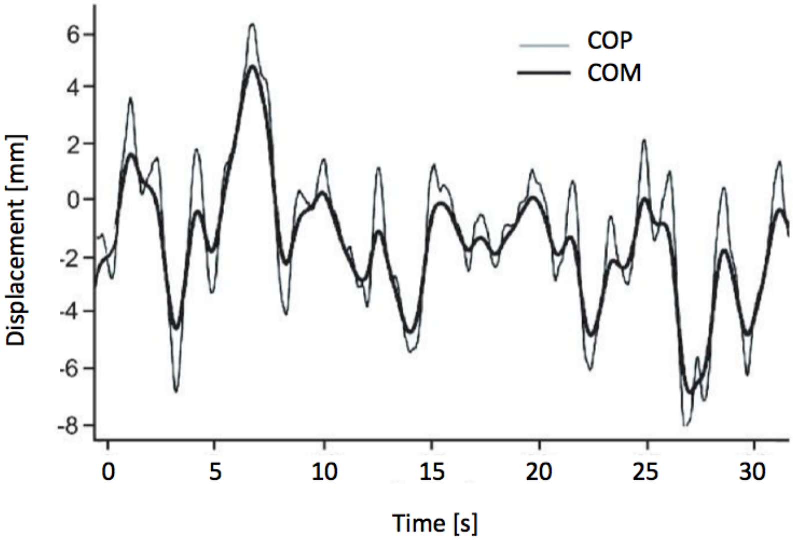

Figure 3.3: Typical displacement trajectory of COP and COM of a healthy individual. Figure adapted from [BMRS02].

vector is at all times within the COP [WPP+98]. The two parameters dCOM and dCOP describe the distance between the ankle joint and the respective position of the COP or COM [ibid.]. If the body sways in an anterior direction and the COM is in front of the COP (A), the body performs plantar flexion by pressing the forefoot into the ground and thus moving the COP forward [ibid.]. This correction results in a posterior direction of the pendulum (B), which has its pivot point in the ankle joint of the human body [ibid.].

In order to describe the complex problem of postural stabilization, the model of initial stiffness was further developed [WPRI01]. This was based on the realization that the oscillation of the COM is in phase with the COP movements and on the consideration that afferent and efferent delays of active equilibrium control are incompatible with the phase locks [WPP+98]. The CNS adjusts the muscle tone at certain balance control points that the stiffness constant is sufficient to control the large inertial load against the attempts of the gravitational force to tilt the pendulum [WPRI01]. One conclusion points out that stabilization of standing still is achieved solely by the stiffness of the ankle muscles without a significant active or reactive component, except for the background adjustment of the stiffness parameters. They call this mechanism passive torque [WPIG03].
Experimentally, no afferent and efferent neuromuscular delay estimates between COM and COP could be demonstrated, which is why purely reactive muscle control appeared to be unlikely [WPP+98]. This finding was reinforced because the effectiveness of active and reactive control mechanisms is limited by latencies in the low-pass characteristics of the muscle and the motor loop [IM07].
Muscle stiffness was estimated from the torque and the sway angle of the ankle joint [WPRI01]. These yielded a correlation coefficient of r=0.92 [ibid.]. Gage et al. [GWFA04]

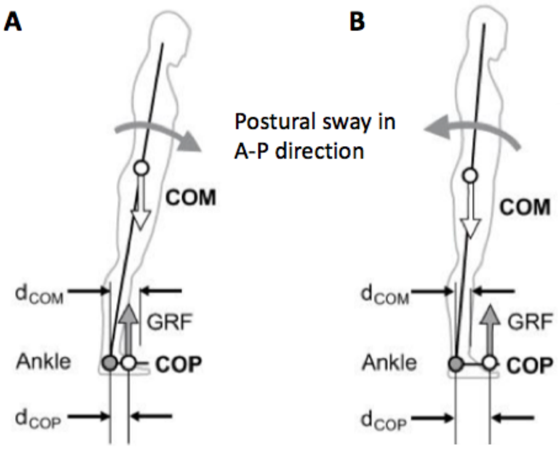

Figure 3.4: The interaction between COM and corresponding COP excursions. Figure adapted from [Ruh11].

were also able to demonstrate a strong correlation between the COP and COM migration and their accelerations in the AP and ML direction. These results are consistent with those of the simulation of the stiffness model by Winter et al. [WPRI01].
Several models for postural control have been based on the ankle stiffness model and used it as a basis. The advantage of this model, and probably a reason for its popularity, is that when most postural variations occur around the ankle, the position of the head in space, the COM in space, or any other point of the body in space are trivially related [Ruh11]. This would facilitate the integration of sensory information from multiple sources [ibid.]. Recently, however, the model has often been criticized and presented as overly simplistic [MMP05]. It has been argued that additional active torque is necessary to stabilize the human body as an inverted pendulum which centre of rotation is the ankle joint, since passive torque is not sufficient [Hof98]. The theoretical stiffness values in the ankle joint are about 500 Nm/rad [ibid.] and thus four times lower than the experimentally measured value of 2000 Nm/rad [MS02]. These results show the physics for the in-phase relationship between COM and COP trajectory rather than by control patterns of the human body [Ruh11]. In addition, the inverted pendulum can be stabilized even with low intrinsic stiffness [ibid.]. This suggests that muscle stiffness is not the only dominant factor in postural control [ibid.]. Casadio et al. [CMS05] showed in their work that the intrinsic ankle stiffness, if it is below the critical stiffness, is not sufficient and an additional active stabilization mechanism is required to compensate for the insufficient stiffness. However, otherwise no active stabilization is necessary [ibid.]. Since the intrinsic ankle stiffness reached only 64±8% of the critical stiffness, additional neural control is likely [ibid.].
Other experimental results are consistent and provide further evidence of the dominant role of the active control moment in balance control [ibid.]. A feedback control model was used to collect stimulus-response data for bipedal posture [Pet02]. Postural stiffness, damping, and feedback time delay defined in the model were estimated so that the

transfer functions could best match the collected stimulus-response data [Ruh11]. The passive intrinsic stiffness and damping parameters were only 10% of the value of the active stiffness and damping parameters [ibid].

The reverse conclusion is that the model of the human body as an inverted pendulum still exists. However, active neural control seems necessary because the passive torque cannot maintain postural control by itself.

### 3.2.2 Body Sway

The human body never stands completely still in an upright position for a long period of time. It always moves a little. These movements can be distinguished in horizontal movement directions AP and ML. Consequently, a frequency of the body sway is to be recorded when considering the change in direction of movement. Krishnamoorthy et al. [KSL02], state that according to Kingma et al. [KTC+95] and Zatsiorsky & King [ZK98], the typical frequency of the body sway is about 0.3 Hz. This is contradicted by Rogers et al. [RWLF01], because the human being does not have a certain frequency in the body sway, but oscillates in a range that goes beyond 1.5 Hz. Young healthy subjects in their study showed the maximum amplitude at slightly less than 0.2 Hz [ibid.]. It is understandable that this is a relatively envious frequency, since the human body is relatively long as an inverted pendulum and fast changes of direction are difficult to implement. But this does not allow to conclude a fixed oscillation frequency. Jeka et al. [JSD97] analysed mean COP displacement frequency and mean head displacement frequency of five subjects (3 m, 2 f) between 20 and 39 years old which were physically active. Both frequencies were between 0.2 and 0.4 Hz with a stationary light touch at the finger tip. However, the influence of externally induced vibrations was investigated in several trials. It turned out that the body sway was coupled to the frequencies of 0.1 Hz, 0.2 Hz, 0.3 Hz, 0.4 Hz and 0.5 Hz [ibid.].
The influence on the reduction of the body sway by a given oscillation with a certain frequency was tested on five participants (mean = 26.3 years, SD = 4.6 years) of which five females and four males [WJE11]. The subjects stood in bipedal Romberg's stance with an inter-heel gap of 5 cm and closed eyes on a force plate recording the COP migration [ibid.] Via a marker at C7 of the spine a motion capturing system was used to record its movement [ibid.] The index finger rested in the thimble of a haptic device to maintain light touch [ibid.]. Five conditions got measured while the index finger remained in the thimble and one no-contact condition for control: (i) thimble held by the haptic device at a constant position (stiff) with spring-like force feedback, (ii) sinusoidal 0.3 Hz oscillation, (iii) sinusoidal 0.5 Hz oscillation, (iv) superimposed 0.3 and 0.5 Hz oscillations and (v) biological movement with playback of thimble movements during the no-contact control condition of one randomly chosen trial form each of five other individuals who were not taking part in the experiment [ibid.]. The movements of C7 and COP were very similar [ibid.] In ML direction, no condition had an influence on the movement of the C7 [ibid.]. In AP direction, only the stiff condition had a reducing effect on the sway

[ibid.]. All other conditions increased the body sway [ibid.].
Johannsen et al. [JWH12] assumed similar results and analysed the influence of inter personal light touch (IPLT) on standing balance. 16 healthy adult participants (mean 32.7 y SD 11.9 y, 6 f, 6 m, 2 same-sex pairs, 4 mixed-sex pairs) in different bipedal or tandem Romberg's stance were analysed [ibid.]. The IPLT was either fingertip or shoulder contact [ibid.]. A total of 12 posture-touch conditions resulted [ibid.]. The sway was produced by the movements of the upper trunk by a marker at C7 [ibid.]. Sway was reliably less with IPLT compared with no contact, with two exceptions: in normal stance, shoulder contact with a partner in tandem stance, and in tandem Romberg stance, finger contact with a partner in the same stance, increased sway [ibid.]. Otherwise, the reduction in sway was greater with shoulder than with finger contact [ibid.]. The overall peak coherence frequency was at 2.94 Hz (standard deviation (SD) 0.40 Hz) [ibid.].

## 3.3 Influencing Factors on Light Touch and Postural Control

With regard to the influencing factors, light touch and postural sway cannot be distinguished from each other. This is because both are primarily influenced by somatosensory sensation. In the following, I will present the state of the art with regard to light touch and postural sway on the basis of internal and external influencing factors.

### 3.3.1 Influence of Internal Factors

„Internal“ refers to the human organism and describes all internal components. In doing so, I deal with age, pathologies and the influence of the physical training state.

**Age**
The demographic change in Germany leads to an additional burden on the health care system due to increased fall related injury costs [PF07, HS17]. In addition, the often catastrophic and disabling consequences of fall related injuries make the balance in elderly population a major concern [SH07]. For this reason, it is a national concern to find causes for the increased risk of falling in old age in order to implement appropriate preventive measures with the aim of reducing cost burden. In this context, the influence of somatosensory sensation on gait and fall behaviour in old age was increasingly investigated. These publications provide information on somatosensory sensation in elderly.

Humans have to integrate information from different sensory systems as a task complexity and challenge to increase postural stability, but are primarily dependent on proprioceptive and cutaneous input in order to maintain a normal, calm posture and to cope safely with the majority of activities of daily life [BC04, EK01, LCW91]. Impaired vestibular function, vision, sensation, strength, and reaction time occur with increasing age and are believed to contribute collectively to the increased likelihood of falls

[LRHF99, LS05, LW94]. I deal in the following with anatomical and physiological age-related changes of receptors (subsection 2.1.1) responsible for activating afferent pathways (muscle spindle, Golgi tendon organ, and articular and cutaneous receptors).
*Muscle spindles* are stretch-sensitive mechanoreceptors that provide the nervous system with information about the muscle's length and velocity of contraction and joint position as well as joint movement (subsection 2.1.1) [SH07]. With age (newborn-81 y), human muscle spindles (n=659 muscle spindles) show an increased thickness of the spindle capsule and a loss of total intrafusal fibres (fig. 2.5) per spindle [SF72]. Additionally the total number of spindles decreased in the biceps brachii for older adults (n=21 total samples, n=5 subjects, age=69-83 y) compared with younger adults (n=36 total samples, n=10 subjects, age=19-48 y) [LETPD05]. This results in a decrease of joint position sense (JPS) in the ankle in weight bearing [You05] and the great toe [KBW78]. It is important, that modifications are not uniform across all muscles or intrafusal fibre types [SH07].
*Golgi tendon organs* (subsection 2.1.1) provide additional proprioceptive information that is important for accurate assessment of joint movement while it is located at the muscle-tendon interface and relays afferent information about tensile forces within the tendon [SH07]. Proprioception provided by Golgi tendon organs can be assessed clinically through examination of awareness of JPS and joint kinaesthetic (motion), which is determined by establishing a threshold at which motion is detected during various velocities and ranges of movement [ibid.]. Several researchers [MS05, BSWH01, You05, KBW78] investigated the JPS on different human joints with a significant difference between young and older adults. A loss of proprioception is associated with a higher risk of fall [SH07].
*Cutaneous mechanoreceptors* innervate glabrous or hairless skin and deliver important feedback about the environment and proprioception. Plantar cutaneous mechanoreceptors provide information about the site and force of weight-bearing activities [RWM95, KI02, Per06] and have an influence on the muscle activity of the lower limbs [BKK89]. The total number of Pacinian corpuscles decreases with increasing age [CM58] as well as vibration perception thresholds and perceived magnitude of vibration at frequencies (100-300 Hz) that activate Pacinian channels [VBG02]. Older healthy adults (n=5, 68.6 y) required a significantly ($p<.001$) greater amplitude (19.2 dB) of 250 Hz vibration to achieve the same sensation-perceived magnitude as younger subjects (n=5, 23.5 y) [ibid.].The concentration of Meissner's corpuscles decreases with increasing age [BWD66] as well as the size and number [IGG$^+$03].
A combination of these factors leads to weak balance control. A study of balance control in older (80 years) people (56 m, 120 f) found that ankle flexibility, plantar toe flexor strength and plantar sensation are significant ($p<.05$) and dependent indicators of balance control in stance [BMK04]. Therefore the parameters were investigated by sway on floor (trajectory length), sway on foam (trajectory length) and maximum balance range (distance of hip displacement in anterior direction) [ibid.].

### Gender

With regard to gender, there are different sensibility thresholds. Through a cutaneous electrical perceptual threshold (EPT) dermatomes can be stimulated. In a study of 29 healthy women and 16 health men (21-76 y), woman had across all ages lower group mean EPT than men (p=.0001) [LjLRW10]. The cutaneous electrical stimulation occurred across 28 dermatomes (fig. A.2 in the appendix) of the whole body [ibid.]. Women younger than age 50 years had lower mean EPT than those older than age 50 years (p=.008) [ibid.]. There was no group difference between younger and older men (p=.371) [ibid.].

Regarding cutaneous foot sensitivity, which plays a significant factor in proprioception (section 2.2.5), the literature is not entirely clear. Meh and Denisilic [MD95] dealt with the influence of age, sex, height and the psychotropic drug diazepam on the perception of vibrations. 92 subjects aged 10-71 years, including 46 female and 36 male subjects, were tested [ibid.]. The vibration disappearance threshold, vibration perception threshold and vibration threshold at 100 Hz were measured at seven reference points of the upper and lower extremities [ibid.]. The results show no significant difference with respect to gender, which is confirmed in the current literature [GSM16, SMSO09, SSM09, SGM17]. In contrast, Schlee et al.[SSM09] refer to a conference contribution by Sterzing, Uttendorf and Henning (2004), which reports a consistently lower threshold for women compared to men. Consequently, no clear statement can be found in the literature regarding the influence of gender on foot sensitivity. Looking at the state of research in purely quantitative terms, the majority of studies prove that foot sensitivity is gender independent. Few studies show a gender influence in old age.

### Diseases

Nearly every neurological disease affect both the sensors of the sensory motor system and their afferents have an influence on the human postural sway [HEM15]. The most common disease of this kind is caused by diabetes mellitus [ibid.] This is due to the fact that diabetes mellitus is one of the most common metabolic diseases in the western world [ibid.].

In peripheral polyneuropathy mainly long and fine peripheral nerve fibres are destroyed [ibid.] This often leads to numbness or tingling in the limbs, especially in the feet [ibid.] However, diabetic polyneuropathy can manifest itself not only in a loss of sensitivity, but also in sensations such as pain [ibid.] One consequence of this can be the diabetic foot. This is a syndrome of pathological changes based on a painless sensory neuropathy in diabetes mellitus [ibid.]. The sensation of pain is often greatly reduced or completely absent, so that even large and deep wounds are not perceived [ibid.] Wounds often occur unnoticed in trivial accidents, after improper foot care, when there are stones in the shoe, when the foot is put under too much strain or even when the tips of the toes of the foot bump into the shoe or against edges [ibid.]. Due to the numbness the ability to keep the balance is impaired.

**Training**
Since the turn of the millennium, competitive sports have increasingly relied on proprioceptive training. Often, training is combined with whole-body vibration (WBV). WBV is a training method that exposes the entire body to mechanical oscillations while standing on a vibrating platform [Coc11]. There is still an ongoing debate in literature, whether there are additional effects of WBV on muscle fitness and muscle performance in comparison to conventional exercise [Rit09]. On one hand, there is evidence for an additive effect of WBV beyond that of conventional exercises regarding motor control [ADPCP+12, BDC+07]. On the other hand, there are several other studies, in which WBV-induced performance improvements could not be found [dRvRS+03, KBCM06]. However, the differences in the results are due to the methods used and, above all, to special areas of application. Ritzmann et al. [RKBG14] have conducted a control study with n=38 participants. The participants were either assigned to the WBV group or the equivalent training group [ibid.]. Number of sets, rest periods, training duration and task-specific instructions were matched [ibid.]. Beside balance control (COP displacement) local static muscle endurance and jump height were assessed before and after the training period [ibid.]. WBV caused an effect on balance control (pre vs. post WBV) with a reduction of COP displacement of 13%, (p<.05) and no effect for the control group (6%, p=.33) [ibid.]. Conclusion is that a training program that includes WBV can provide supplementary benefits in young and well-trained adults compared to an equivalent program that does not include WBV [ibid.]. Consequently, no clear statement can be found in the literature regarding the influence of proprioceptive training an balance control. But since there is a lot of proof in literature and most of pro athletes stick to proprioceptive training, I will take into account the current state of training when recruiting subjects.

### 3.3.2 Influence of External Factors

The results of studies on the influence of temperature are contrary. For this reason Schlee et al. [SSM09] investigated the effect of different temperatures on vibration sensitivity. For this purpose 40 test persons (n=20 m, n=20 f) were recruited. The vibration perception threshold was measured at 200 Hz at the heel, big toe and the 1st metatarsal head of both feet. All measurements were performed with the basic temperatures 28,3C±5-6°C. The results showed a significantly lower threshold when the feet were heated and a significantly higher threshold when the sole of the foot was cooled. Also Germano, Schmidt and Milani [Ger16] found an increasing vibration perception threshold with decreasing sole temperature. The investigations of Hilz et al.[HAH+98], among others, contradict this. Both the different anatomical regions and the different vibration frequencies may be responsible for the contradictory results. Currently, the study results of Schlee at al. [SSM09] are of great importance, and the influence of temperature is relevant.

# Chapter 4

# Idea of the Thesis

The approach of this study, to see an effect of a haptic stimulus provided by a wearable device on postural sway, is initially supported by Jeka et al. [JEBL96] who could prove the light touch cue not by an earth fixed but by a lightly mobile device (subsection 3.1.1). After it was proven that light touch has a decreasing effect on body sway not only by the finger pad but also by other parts of the body (subsection 3.1.2) Rogers et al. [RWLF01] investigated the influence of a weight (0.25 N) on the shoulder on postural sway but could not prove any effect. However, this weight did not provide any haptic feedback of body sway or dynamic stimuli.
To find out whether an external artificial haptic stimulus has a decreasing effect on postural sway, Wing et al. [WJE11] imitated the haptic feedback by characteristic movements of a haptic device (frequencies of 0.1 Hz, 0.2 Hz, 0.3 Hz, 0.4 Hz and 0.5 Hz) at the finger pad. This had no influence on ML direction of postural sway, in AP direction postural sway even increased. A similar approach of the moving haptic device has been developed by Johannsen et al. [JWH12]. They investigated the influence of IPLT on postural sway, since the human body is known not to stand completely still. The IPLT in turn had, with one exception, a reducing effect on the postural sway with frequency of the peak coherence in the AP direction of ~0.3 Hz (subsection 3.2.2).
One area of the human body particularly well suited for light touch is the forearm at the transition to the wrist (subsection 3.1.2). Fast adapting (FA) receptors at the forearm include Pacinian corpuscles (vibration) and Root hair plexus (touch, pressure). They are very sensitive to light touch, vibration, and movement between the skin and a contact surface because the epidermis (first layer of the skin) is very thin compared to the finger pad [JH92] (subsection 2.1.1). In addition, this area of the forearm is located relatively far in the middle of the C6 dermatome and thus an overlapping of the dermatome can be excluded (section 2.3). This is advantageous, because in this way spinal reflexes can be limited, since mechanoreceptive and proprioceptive alpha and beta afferents with collaterals of their central extensions are connected in different laminae (thin layer of tissue) of the ipsilateral spinal cord with higher neurons (subsection 2.1.3).

For this reason, the wearable device should be worn like a watch for the measurements. This has the advantage that the skin there reacts particularly sensitively to haptic stimuli. In addition, the position offers the advantage that a device can be worn like a wristwatch and the body posture during measurement corresponds to that of a normal bipedal free stance. Pressure and vibration are generated once as stimulus. In this way both the Pacinian corpuscles and Root hair plexus are stimulated. These are also stimulated by a light touch. Since both receptors are fast adaptive (FA) (subsection 2.1.1 and fig. A.1 in the appendix) the stimulus must be dynamic. A vibration frequency of 150 Hz is specified for the Pacinian corpuscles. This corresponds to the sensory threshold (fig. 2.4). Vibration is applied once constantly and once at a frequency of 0.3 Hz, which corresponds to the entrainment of the IPLT (subsection 3.1.2). As frequency for the pressure a sinusoidal frequency of 0.3 Hz is defined, with an amplitude $<1$ N, which corresponds to light touch. In order to analyse whether the location on the upper arm generates a light touch cue with an earth fixed contact, this is examined with a force sensor.

The following experimental conditions are derived:

(i) control condition (cc) without light touch contact or tactile stimulus

(ii) constant vibration (cv) wearing haptic device with constant vibration

(iii) device off (do) wearing haptic device without any stimulus

(iv) earth fixed (ef) Light touch with earth fixed reference point

(v) sinusoidal force (sf) wearing haptic device, sinusoidal vertical force stimulus

(vi) suinusoidal vibration (sv) wearing haptic device with sinusoidal vibration

In order to exclude internal influencing factors, only young healthy subjects were invited as participants, since age has the greatest influence on somatosensory system and consequently on postural control, apart from neurological diseases (subsection 3.3.1). All participants took bipedal stance with a distance of 5 cm between the feet. To increase postural sway participants had to close their eyes during all conditions. Duration of one trial was 30 s [SCGS13]. Since the influence of light touch at the wrist on the measured variables rambling and trembling had not been investigated, an analysis of the experimental conditions on these parameters is carried out.

## 4.1 Hypotheses

Since non-earth fixed haptic devices have a decreasing effect on the postural sway by light touch, I formulate the following major research questions and hypotheses:

**1st research question:**
Is there a light touch effect with an external fixed object at the wrist?

$H_0$: A light touch cue of an earth fixed reference point at the wrist has no reducing effect on body sway.
$H_1$: A light touch cue of an earth fixed reference point at the wrist has a reducing effect on body sway.

**2nd research question:**
Can a wearable device at the wrist affect body sway, and is this effect as effective as with an earth fixed object?

$H_0$: A light touch cue of a wearable device has no reducing effect on body sway.
$H_1$: A light touch cue of a wearable device has a reducing effect on body sway

**3rd research question:**
Is the effect of the haptic device different among the three different stimuli conditions?

$H_0$: Different haptic light touch cues of a wearable device have no reducing effect on body sway.
$H_1$: Different haptic light touch cues of a wearable device have a reducing effect on body sway.

# Chapter 5

# Wearable Haptic Device

In this chapter I will introduce the wearable device that is supposed to perform light touch cues for conditions listed in the previous chapter 4. It is an own construction and was created especially for the measurements in this work. The device was not created on a clean sheet, but was already developed in a first version as a prototype. On this basis I have further developed the device with focus on comfort and ergonomics to minimize haptic disturbances as much as possible and add the modus of vibration.

**Requirements**
The device has the requirement to apply haptic light touch stimuli at the transition from the forearm to the wrist while standing upright. The natural upright position with relaxed, hanging arms should be restricted as little as possible. The device is required to execute the following haptic stimuli:

- sinusoidal contact force $\leq$1 N
- vibration of 150 Hz with a contact force $\leq$1 N
- vibration of 150 Hz as an interval with a contact force $\leq$1 N

## 5.1 Design

**Predecessor**
As I mentioned before, the device for this study was based on a predecessor in figure 5.1. The first prototype was in style of a watch but had some disadvantages in comfort which had a negative effect on the haptic stimuli of the light touch. The contact surface of the case was very small (fig. 5.1 on the right), which increased the pressure on skin due to the fastening and most likely far above the 1 N of the light touch cue. In addition, these contact surfaces were very close to the stamp, the component that executed light touch. Thus, the probability is very high that the receptive field of the cutaneous mechanoreceptors was activated in advance to the light touch. Due to the dimension that device was higher than wider and had the cable outlet on the top, additional pressure on the

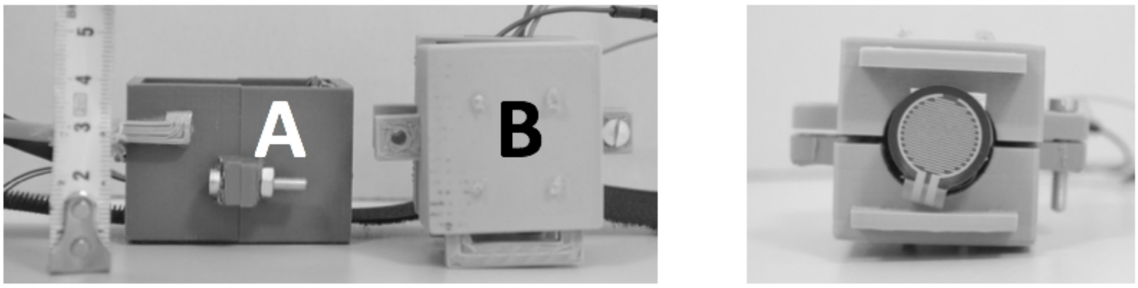

Figure 5.1: On the left (A) the wearable device and (B) predecessor from side angel. On the right the predecessor from bottom angle with sensor and contact surface on top and bottom.

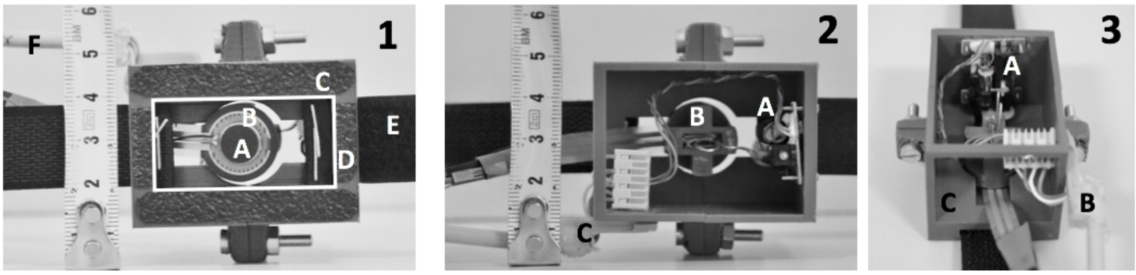

Figure 5.2: In picture **(1)** is the wearable device form bottom angle. (A) is the vibration motor, (B) the FSR, (C) grip tape, (D) the white rectangle is the non-contact area, (E) Velcro belt and (F) adhesive cables. In picture **(2)** is the wearable device from top angle. (A) is the servo motor, (B) stamp with staple and (C) adhesive cables. In picture **(3)** is the wearable device from front angel. (A) is the servo motor, (B) adhesive cables and (C) the cable outlet.

contact surface was created by the leverage when the device was turned by $90^\circ$ when standing in upright position during the measurement. This in turn could have had a disturbing effect on the sensitivity.

**Wearable Device**

The case (fig. A.5 and A.6 in the appendix) and stamp (fig. A.7 in the appendix) were constructed with Autodesk Fusion 360 [version 2.0.8624 for macOS] as a Computer-Aided Design (CAD)-model. The models were 3D-printed with a Cura Ultimaker 2+ and polylactide acid filament (PLA) (TPU95A).

The contact surface of the case with skin is $11.94\,\mathrm{cm}^2$. So that the Velcro belt can be tightened as loosely as possible. The contact surfaces are covered with a grip tape made of rubber that the device cannot slip. The non-contact area where the stamp produces the light touch cue is 2 cm x 5 cm to avoid contact with a receptive field. The bottom of the case has a hole with a radius of 1 cm to provide a port for the stamp which is not too wide so that the stamp can be guided in it. A cut-out provides space for the FSR and vibration motor connection. The height of the case is determined by the circuit board of

the servo motor, as it must be mounted vertically. One end of the case is open to provide cable outlet to the side. On both ends of the case are fitted holes for the Velcro belt to be fixed. The case dimensions are 5.3 cm x 3.8 cm x 3.7 cm. Since the case consists of two 3D-printed parts, these are fixed by two screws with nuts. The wall thickness is 0.2 cm to ensure stability and save weight.
The servo motor [Spektrum 2.9-Gram Linear Long Throw] is a long throw servo that changes its position by rotating a threaded rod. To move the stamp it is mounted via a staple to the servo motor. Contact surface of the stamp is a circle with radius of 0.9 cm. This is the same size as the FSR [Interlink Electronics FSR402] which measures pressure by force-to-voltage conversion described by equation A in the appendix. The FSR is fixed on the bottom of the stamp to measure the pressure of the light touch cue. On top of the FSR is the vibration motor [Brunswick DC 3V, 10 mm x 2.7 mm] which has a smaller size with a radius of 0.5 cm. Since the sensor does not measure pressure with its entire surface but still has an outer ring without resistors, it is difficult to measure the pressure on the relatively soft tissue layers of the skin of the forearm. For this reason the vibration motor is mounted with double sided adhesive tape on the sensor which has a smaller radius of 0.5 cm and a height of 0.27 cm. The vibration motor contacts the skin and transfers pressure to the sensor. This enables that the vibration is transmitted directly from the motor to the skin if vibration is required.
The Velcro belt consists of two parts that can tack each other. One end of each part has been enlarged by tacking needles so that it acts as a stop after threading it into the hole in the case. To prevent the servo motor, vibration motor and FSR from being destroyed by pulling on the cables, they are attached to the case with adhesive.

The controlling part of the wearable device consisted of an Arduino Uno SMD single-board microcontroller to compute the written code, an H-bridge [DRV11873 Brushless Driver EVM] to switch the polarity of voltage applied to the load for vibration motor and a power supply to provide 3.3 V for the servo motor and FSR as well as 5.0 V for the vibration motor. A schematic is in figure A.8 in the appendix. The code was written in C and C++ for Arduino.

# Chapter 6

# Methods

In this chapter methods used for this work are described. Here first the participants 6.1 and criteria for inclusion and exclusion are shown followed by the setup 6.2, procedure 6.3 and data post processing and statistical analysis 6.4.
For reasons of the COVID-19 pandemic in 2020, there were specific hygienic and behaviour guidelines set by the Bavarian State Government the Technical University Munich had to follow. These guidelines, which I had to follow during the measurements as well, consisted among others wearing a face mask while being in public rooms to prevent spray and a minimum spacing of 1.5 m between each other to reduce the risk of infection. When these guidelines affected the procedure from its origin I will explicitly mention them.

## 6.1 Participants

This work is a crossover study of postural sway in human upright stance under the influence of various haptic stimuli. For this study, 4 subjects were recruited via a non-probability sampling procedure. The study is limited to subjects aged 18-29 to get a group of young students and get a clean line to middle aged adults. Neurological diseases affect the sensory motor system and their afferents [HEM15] and consequently postural sway. For this reason, at the beginning of each measurement the subjects were asked if they suffer from known neurological diseases or if they have diabetes mellitus. Already one of these diseases would have led to exclusion from the measurements. General criteria for exclusion of of user studies are listed below. Because these guidelines were followed, most likely internal influencing factors were excluded.
After diseases of the sensorimotor system, age probably has the greatest influence on the balance. The results of Liu et al. [LETPD05] and Swash and Fox [SF72] show that in older adults compared to younger adults (19-48 y) the capsule thickness of the muscle spindles increases and the number of intrafusal fibres of the spindle decreases. In addition, the total number of muscle spindles decreases with age and the JPS of various joints decreases due to degeneration of the Golgi tendon organs [MS05, BSWH01, You05, KBW78] which causes less balance during stance. Cutaneous mechanoreceptors decrease in total with

age (n=5, 68.6 y) and show an increase in the sensitivity threshold to younger adults (n=5, 23.5 y) [VBG02].

Additionally, the amount of proprioceptive training has an influence on human balance [RKBG14]. Although there are partially contradictory study results [Rit09], the training of balance is taking a constant place in more training plans and many professional athletes swear by the methods. For this reason, the athletic activity of the subjects was surveyed and for balance training in particular was asked. In combination with the influence of age on postural control and increased training behaviour, the age of the subjects was limited to a life span of 18-29 years. Since it is to be assumed that the amount of sports activities decreases with the start of a job life, the limited age was primarily aimed at students. In this way, a sample of subjects as homogeneous as possible with regard to health, age and training level could be generated in advance. The results of the questionnaire at the beginning of the measurement show that none of the subjects did balance specific training and all of them are engaged in outdoor sports.

Even though gender has no influence on postural control [GSM16, SMSO09, SSM09, SGM17], the sample (n=4) was equally distributed (female n=2, male n=2) and the anthropometric results show a good representing sample of the german population aged 18-30 years.

Guidelines of the Bavarian State Government, to which the Technical University of Munich adhered, provided for a minimum distance of 1.5 m to minimize the risk of infection. This could not be maintained continuously during the procedure. For this reason, only test persons from the supervisor's household were admitted to the study.

Criteria for inclusion:

- age between 18 and 29 years
- no injury of musculoskeletal system for the past three months
- no known neurological disease
- from the test director's household
- compliance for this study
- written consent to participation

Criteria for exclusion:

- acute or chronic general infection (fever, infectious diseases)
- metabolic disorders (diabetes mellitus)
- dizziness
- pain of musculoskeletal system
- thrombosis, haemophilia, peripheral arterial occlusive disease
- alcohol abuse, pain medication intake (within the last 24h)

## 6.2 Setup

The measurements took place in the interaction LAB of the professorship for Human-centered Assistive Robotics of the Technical University of Munich from. The setup, shown in figure 6.1, consisted of one AMTI force plate [AMTI OPT400600-2KS-STT] six channels (3 force, 3 torque) and a COP accuracy typically less than 0.5 mm [1]. On the force plate was a cross marked in the centre with 5 cm wide duct tape to mark the position of feet as shown in figure 6.2 (2). The inter heel distance varies in research between different studies but is mainly 5 cm [PN15]. The upright stance with an inter heel distance represents the natural upright position of human in the best way [BT18]. The force plate was connected via analogue cable (six four-arm strain gage bridge inputs) to the amplifier [OPTIMA SIGNAL CONDITIONER] at the work station. Digital output of the amplifier was via USB 2.0 to the computer [Windows 10] at the work station. There were two chairs, one as a handle for balance emergencies positioned on the contra lateral side wearing the haptic device to have a free hand for emergency and the other one for cable support as well as the device for haptic stimulus (chapter 5). The distance between force plate and work station was 200 cm. This kept the cable connection short and separated the subjects on the force plate from the work station in space and the minimum spacing af 1.5 m was kept. The subject's viewing direction and therefore the orientation of the force plate was in opposite direction to the work station to provide optimal cable connection whether wearing the device on the right or left wrist and the least haptic distractions form cable movements. The force and torque sensor Nano17 [ATI INDUSTRIAL AUTOMATION] was connected via 12-pin analogue to the Net Box (9105-NETBA). Between Net Box and PC was a switch [NETGEAR ProSafe GS108P] connected via Ethernet. The Nano17 sensor was applied with double sided adhesive tape measuring z-axis in horizontal direction on a tripod with extendable legs to adjust the height for each subject as shown in figure 6.2 (1). The subjects wore earmuffs to protect from noise distractions of the motor in the haptic device as well as a face mask for hygienic reasons. The work station consisted of a PC [Windows 10] with installed Visual Studio 2019 to control the force plate and haptic device. MATLAB [R2019a] was installed to control the Nano17.

To measure body height a thin book with hard cover, a pen and a scale were used. To measure the temperature of force plate and foot soles via radiation FLUKE 63 IR THERMOMETER was used to maintain distance. A temperature of 25°C is recommended according to Schlee et al. [SSM09], because a temperature deviation of 5-6°C of the food already has an effect on foot sensitivity. A digital room thermometer was used to measure the room temperature.

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[1] https://www.amti.biz/AMTIpibrowser.aspx (last retrieved at 07.06.2020)

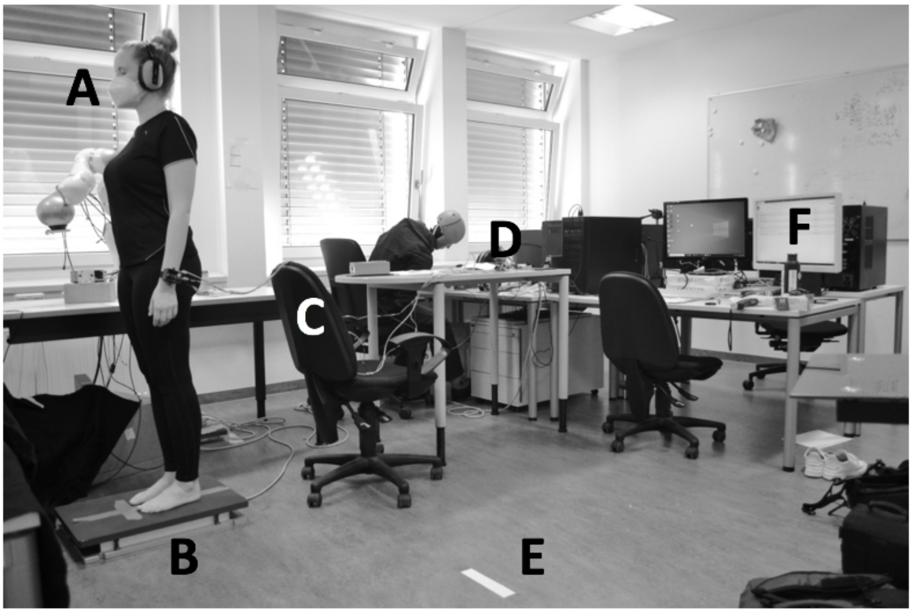

Figure 6.1: The setup for the measurements with (A) participant wearing the haptic device, ear protection, a face mask and standing in upright position with eyes closed on the (B) force plate, (C) chair for cable support, (D) controlling part of wearable device, (E) mark to set the minimum of 1.5 m distance between participant and (F) work station.

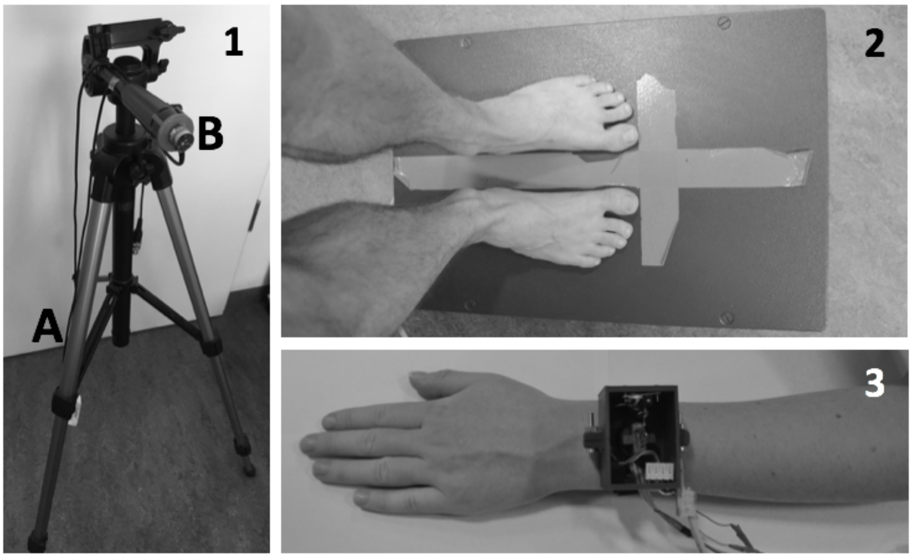

Figure 6.2: In picture **(1)** the (A) tripod with (B) Nano17 sensor. In picture **(2)** the force plate with exact foot position for the measurement. In picture **(3)** the wearable device worn on the wrist.

## 6.3 Procedure

Table 6.1: *Overview time table of measurement*

| | Time [min] | Content |
|---|---|---|
| Introduction | 10 | Welcoming, paper work, questionnaire |
| Test | 5 | Test trial, answering questions |
| Measurement | 25 | 4 different interventions each 6 trials |
| Break | 3 | |
| Measurement | 15 | 2 interventions each 6 trails |
| Ending | 5 | exchanging information about study |

### 6.3.1 Preparation

All interventions were block randomised with Microsoft Excel (Version 16.32 for macOS) for each participant in advance, except control measurement in the beginning and earth fixed at the end for organizational reasons.
After welcoming the participants, they were requested to wash their hands in the restroom on the floor for reasons of hygiene. Consequently they got orally informed about the goals, contents and risks of the study as well as behaviour guidelines of COVID-19 pandemic. After answering upcoming questions, information and declaration of consent in figure A.10, A.11, A.12, A.13, A.14 in the appendix were handed over and signed by the respective participant. Demographic data was collected via experimental protocol in figure A.15 in the appendix as well as room temperature. After finishing a short questionnaire body height was measured. Therefore the subjects were asked to take off their shoes and socks to stand backwards barefoot in upright position on a wall in the lab. To maintain the minimum distance of 1.5 m the subjects had to mark their body height on their own. Under guidance of the test director the participants placed the book on top of their head in parallel position to the floor and placed a mark with the pen on the book's upper side on the wall. Test director checked from the side the right position of the book. Afterwards the distance from bottom to mark was measured with a scale and the thickness of the book was subtracted to get body height. From this point on the subjects stayed barefoot to reach a steady foot temperature during the measurements. According to Schlee et al. [SSM09] a temperature deviation of 5-6°C already has an effect on foot sensitivity.

Next step was to demonstrate the measurement. Therefore the exact foot position (fig. 6.2) was demonstrated with the hallux (big toe) limited by the line in front and on the sides as well as the heel touching the line on the inner side. Posture was upright, arms and hands hanging relaxed on the sides, head and eyes straight ahead as shown in figure 6.1 (A). Because of closed eyes during the measurement the use of a table as a rescue handle was explained. Stepping on and off the force plate was executed with side steps to move the cable the least. Followed by answering upcoming questions the participants practiced the procedure once. If it was not correct the procedure got repeated. Afterwards the procedure with earth fixed reference point to maintain contact at the wrist was demonstrated. Posture was the same like with the haptic device. Procedure was practiced by the participants once and repeated if it was not correct. To get a feeling what the pressure of 1 N is all participants had to run a test of 30 s with the force sensor monitored on the work station to see the applied pressure when reaching 1 N. Due to randomisation and for logistical reasons, the condition of ef has been implemented either too as first or last condition. In order not to lose the feeling for the 1 N, the test trial was always performed directly before the measurement of the condition ef. In the next step ear muffs were handed over which the subjects applied. A sound test was followed to see whether the subjects could understand the test directors instructions with ear muffs on. Subsequently the temperature of the barefoot sole via radiation on right and left foot's heel were measured. The participants stood backwards in front of the test director beside the chair close to the force plate for standing support. The test director stood at the work station with a minimum distance of 1.5 m. At the test directors request the subjects bent their right and left knee one after the other to show the respective foot sole. With the laser pointer of the radiation thermometer the centre of the heel was aimed and measured. Afterwards the temperature of the force plate was measured. The last step of preparation was to zero the force plate via hardware.

### 6.3.2 Measurement

As I described earlier (subsection 6.3.1), the interventions were block randomised except for control measurement and earth fixed. In the following I describe the procedure with control condition in the beginning.

The first condition was control condition (cc) (chapter 4) in which the participants stood free without haptic device or earth fixed reference point. The participants put the ear muffs on, stepped on the force plate and assumed the requested posture. At first I gave instruction to close eyes and started recording data for exact 35 s. When the first trial was finished I gave the audio call to the participants to open their eyes and step off the force plate and a break of 30 s passed by in which I saved the recorded data and participants could relax. This procedure repeated for a total of six times. After that I checked data to see if the recording worked fine. Subsequently I applied the haptic device on the subjects preferred wrist. The device was placed upside down on one of the chairs with the contact zone facing upwards. I asked the participants to place their arm with the dorsal side (like a watch) and a relaxed manner on the device and fastened the belt that it had a slight permanent contact with the skin and was not to tight to apply unnecessary force. During this step the minimum distance of 1.5 m could not maintained. The worn haptic device is in figure 6.1 (A) and figure 6.2 (3). After that the subjects walked on the force plate and assumed the required posture again. Meanwhile I placed the cable on the chair (fig. 6.1 (C)) between force plate and work station for support. After that I gave the instruction to the participants to close their eyes and started the trial. As I mentioned before, conditions with the haptic device were block randomised in advance. Each trial lasted for 35 s with a break of 30 s afterwards and a total of six repetitions. After the third condition the experiment had a two minute break for subject's and haptic device's rest. After the break two more conditions with the haptic device got measured with the same procedure before. Subsequently the participants were allowed to take off the ear muffs and I took off the haptic device and asked the subjects to assume the required posture for measurement with the feet in position, upright stance, head and eyes ahead and relaxed arms. Afterwards I placed the Nano17 applied to the tripod on the side where the subjects wore the haptic device hand adjusted the height that the Nano17 got in contact at the point of the forearm where the device has been before. Afterwards I asked the subjects to put on the ear muffs again, to assume the posture, get contact to the reference point, close their eyes and started the measurement with a total of six trials of 35 s each and breaks of 30 s in between. The last step was to measure the temperature of the feet sole's the same way I did before the measurement (subsection 6.3.1) and to calculate the body weight as the mean value of force in z-axis of the first trial. After that the measurement was completed.

## 6.4 Data Post Processing and Statistical Analysis

After each trial, the recorded data was saved. In a first step after the measurements, it was checked whether the cues of the haptic device, which stimulus was triggered at which exact measurement time, were correctly stored in the force plate data. For this purpose, a frequency of 0.3 Hz was verified for the sinusoidal stimuli. In a second step, the data for each recorded trial was smoothed with the software MATLAB [version R2019a] as in section 2.2.2 and the paragraph below, with a low-pass Butterworth filter 4th order of 10 Hz cut-off. Then the parameters $COP_x$, $COP_y$ and rambling and trembling in x and y-direction were calculated. In the next step, the data was processed in Microsoft Excel. The trials were shortened from 35 s to 30 s by removing 2.5 s in the beginning and end of each dataset. Consequently the COP-trajectory was calculated from $COP_x$ and $COP_y$. In the next step the root mean square (RMS) (see paragraphs below) was calculated for the parameters rambling and trembling in x and y-direction for each trial and for the COP-trajectory the mean COP-velocity per trial. From the six RMS and mean COP-velocity (six trials) of a subject per condition a mean value was calculated for each subject per condition. This mean value was then used for statistical analysis of overall subjects. If a subject was analysed individually, the six RMS and mean COP-velocity (six trials) of a subject per condition were used for each condition of a subject. For statistical analysis one way analysis of variance (ANOVA) with repeated measures and a significance level p=.05 was used when homoscedasticity and normality were given. The non-parametric alternative to ANOVA was Friedman-Test. When post-hoc tests for pairwise comparisons were needed, Tukey's range test and the non-parametric Games-Howell were used. A detailed description of data post processing and statistical analysis can be seen in paragraphs below.

**Force Plate**

Six components of the ground reaction force (horizontal ($F_X$, $F_Y$, $F_Z$, $M_X$, $M_Y$, $M_Z$) in a right handed coordinate system) were measured using an AMTI force plate. The signals were sampled at 200 Hz for 35 s. 2.5 s in the beginning and ending of each trial were deleted to reduce the measured data to 30 s. COP in ML (X) and AP (Y) directions were computed by:

$$COPx = -\frac{M_y + F_x}{F_z}$$

$$COPy = \frac{M_x - F_y}{F_z}$$

Decomposition of the ML and AP components of COP into rambling (RM) and trembling (TM) was done as described by Zatsiorsky and Duarte in section 2.2.2 with a low pass Butterworth filter 4th order of 10 Hz . IEP were defined as COPx and COPy coordinates when $F_{hor}$=0. RM was estimated as the interpolation of those points using a cubic spline function. TM was estimated as the difference between COPx and COPy and RM. The RMS of each of these parameters was calculated for each trial. After that all six RMS for one parameter per subject were calculated as a mean value. COP-trajectory was computed by:

$$dCOP = \sqrt{(COPx_2 - COPx_1)^2 + (COPy_2 - COPy_1)^2}$$

The distance of COP-trajectory was calculated as the sum of all dCOP and divided by the time of 30 s to get COP-velocity in cm/s.
The data was acquired using Visual Studio software (for Windows 10) and processed using MATLAB (MATLAB_R2019a for macOS). COP-velocity, rambling and trembling trajectories in X and Y directions were quantified by computing the following parameters: (i) RMS and (ii) mean velocity calculated as total COP distance over time. Rambling and trembling were computed for ML (X) and AP (Y) direction.

**Haptic Device**

Two components of the haptic device were measured. Pressure in Newton (N) and amplitude of vibration in micro meter (µm).

**Statistic of Central Tendencies**

For descriptive and exploratory data analysis the mean value, the minimum (smallest value of a distribution) and the maximum (largest value of a distribution) were calculated [BS10]. The arithmetic mean, colloquially known as „mean“ or „average“ is a measure of location that is suitable as an estimator of the centre of a distribution [ibid.]. It is calculated by dividing the sum of all values by the number of values [ibid.].

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i$$

The RMS is calculated as the square root of the quotient of the sum of the squares of the numbers considered and their number [ibid.]. In this thesis I calculated the RMS for each trial (6000 data points) and parameters RM and TM in x and y-direction.

$$RMS = \sqrt{\frac{1}{n}\sum_{i=1}^{n} x_i^2}$$

### Statistics of Variation and Dispersion

The most common measures of variation are SD and variance (VAR), which refer to the arithmetic mean [SR18]. The SD is a measure of the dispersion of the data around its expected value (mean) [ibid.]. The VAR is the average of the averaged squared deviations from the expected value [ibid.]. Due to the squared values and units of measurement, the variance is difficult to interpret [ibid.]. For this reason the root of the variance - the standard deviation - is calculated [ibid.].

$$VAR = \frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2 \tag{6.1}$$

$$SD = \sqrt{VAR}$$

### Test of Normality

The special significance of the normal distribution is based, among other things, on the central limit theorem, according to which distributions that result from additive superposition of a large number of independent influences are approximately normally distributed under weak conditions [SR18].
The Q-Q Plot is an explorative, graphical tool in which the quantiles of two statistical variables are plotted against each other to compare their distributions [ibid.]. The measured values of two characteristics whose distribution is to be compared are each ordered according to size [ibid.]. These ordered data are combined into pairs of values and are plotted in a coordinate system [ibid.]. If the points (approximately) form a straight line, it can be assumed that the two characteristics are based on the same distribution [ibid.].

### Homoscedasticity

In statistics homoscedasticity means that the variance of error terms is not constant [SR18]. The assumption of homoscedasticity is an important component of the Gauss-Markov theorem [ibid.]. The theorem states that in a linear regression model in which the error terms have an expected value of zero and a constant variance and are uncorrelated, the method of least squares is a best linear unbiased estimator [ibid.].
Levene's test is a significance test, which checks for homoscedasticity of two or more

groups [ibid.]. If the p-value of the test is below a previously determined level, the differences in the variances in sample variances are unlikely to have occurred based on random sampling from a population with equal variances [ibid.].

### Analysis of Variance

Normality and homoscedasticity are requirements for ANOVA. In a one way ANOVA for repeated measures, the comparison of variances allows conclusions to be drawn about differences in mean values [SR18]. It compares the variance within the group with the deviation between the groups [ibid.]. Significance then results, the smaller the variance within the group and the larger the variance between the groups [ibid.]. The value of an observation $\mathrm{x}_{\mathrm{mi}}$ is composed of total mean value $\mu$ effect of the factor $\alpha_{\mathrm{i}}$ and error term $\epsilon_{\mathrm{mi}}$. The hypotheses of an one way ANOVA are:

$\mathrm{H}_0\alpha_{\mathrm{i}} = 0$: There is no difference between the groups of the factor.
$\mathrm{H}_1\alpha_{\mathrm{i}} \neq 0$: There is a difference between the groups of the factor.

$$x_{mi} = \mu + \alpha_i + \epsilon_{mi}$$

### Friedman Test

Friedman test is the non-parametric counterpart to the ANOVA with repeated measurements when the sample is neither normal distributed nor the test of homoscedasticity is not significant [EGS10]. The Friedman test tests the null hypothesis that the medians of several measurement repetitions do not differ [ibid.]. The distribution of the test variable K depends on the number of factor levels and the number of persons [ibid.]. K is calculated from the sum of the squared deviations of all factor level rank sums $\mathrm{RS}_{\cdot\mathrm{j}}$ from the value expected below $\mathrm{H}_0$, added over all factor levels [ibid.]. Although the Friedman test shows whether there are significant differences between repeated measurements, post-hoc tests must be performed to determine which measurement times differ significantly [ibid.]. One possible post-hoc test is the Dunn-Bonferroni test.

$$K = \sum_{j=1}^{p} \left( RS_{\cdot j} - \frac{n \cdot (p+1)}{2} \right)^2 \tag{6.2}$$

### Bonferroni Correction

Multiple comparisons problem in statistics refers to the global increase of the type I error probability by multiple testing in the same sample [SR18] The more hypotheses are tested on a data set, the higher the probability that one of them will be (incorrectly) assumed to be true [ibid.]. In case of multiple test problems, a distinction is made between the local alpha level (affecting only the single hypothesis) and the global alpha level (for the entire hypothesis family) [ibid.]. Bonferroni correction is the simplest and most conservative way to adjust the multiple alpha level [ibid.]. The global alpha level is distributed equally among the individual tests [ibid.].

### Post hoc Analysis

With one way ANOVA it is only established that there are significant differences in a group of mean values. The post-hoc tests use pairwise mean value comparisons to provide information about which mean values differ significantly from one another. Or, by means of group-wise comparisons, they make it possible to determine which group mean values are not significantly different. The parametric test is Tukey's range test and the non-parametric test is the Games-Howell test.

### Effect Size

The effect size is the size of a statistical effect. It will be used to illustrate the practical relevance of statistically significant results [SR18]. Eta-squared is a parameter to show the effect size of an ANOVA and calculated as followed where $\mathrm{SS}_{\mathrm{Treatment}}$ is the sum of squares of the treatment and $\mathrm{SS}_{\mathrm{Total}}$ for the total of sum of squares:

$$\eta^2 = \frac{SS_{Treatment}}{SS_{Total}} \tag{6.3}$$

# Chapter 7

# Results

Data evaluation was performed using the integrated development environment RStudio [Version 1.2.1335 for macOS] for the statistical programming language R. Both descriptive analytical and inferential statistical work was performed.

## 7.1 Anthropometry

The anthropometric data of the sample can be found in table 7.1. From this an average age of 26±1.15 years can be seen. A body height of 177±9.5 cm and a mass of 76.05±21.26 kg results in an average body mass index of 23.81±4.71 kg/m$^2$. The age of 25 years, an average body height of 170 cm and an average weight of 61.85 kg among the women, the sample represents the female German population aged 18-25 years (168 cm; 60,9-62,9 kg; status 2013) [Bun19] very well. The male data with an average height of 185.5 cm and 90.25 kg a bit higher with the anthropometric data of the male German population aged 18-30 years (181 cm; 75,7-81,6 kg; status 2013) [ibid.], but the sample (n=4) is representative for the corresponding age groups in Germany.
The subjects stated to wear a vibrating smart watch but rarely a watch on their left wrist. None of the them stated that they did any special balance training or sports that required special balance. They all practice outdoor sports of mountain biking and hiking. The average temperature for the left foot before the measurement was 28.525±1.750°C

Table 7.1: *Anthropometric subject data.*

| | Age [Years] | Body height [cm] | Body mass [kg] | BMI [kg/m$^2$] |
|---|---|---|---|---|
| M | 26 | 177 | 76.05 | 23.81 |
| SD | 1.15 | 9.5 | 21.26 | 4.71 |
| MIN | 25 | 167 | 55.6 | 18.58 |
| MAX | 27 | 188 | 105.6 | 29.88 |

(min=26.6°C (subject 1), max=30.8°C (subject 2)) and after the measurement 28±1.500°C (min=26.4°C (subject 2), max= 30°C (subject 1)), resulting in a temperature decrease of 0.525°C. For the right foot the temperature was 28.675±1.668°C (min=26.4°C (subject 2), max=30.4°C (subject 1)) at the beginning of the measurement and 27.925±1.365°C (min=26.2°C (subject 2), max=29.4°C (subject 1)) after the measurement. The temperature decreased during the measurement 0.75°C. The mean SD of the temperature of the foot sole was 1.570±0.173°C. The average temperature of the force plate at the beginning of each measurement was 26.025±0.896°C (min=24.8°C (subject 2), max=26.9°C (subject 4)).

## 7.2 Rambling In X-Direction

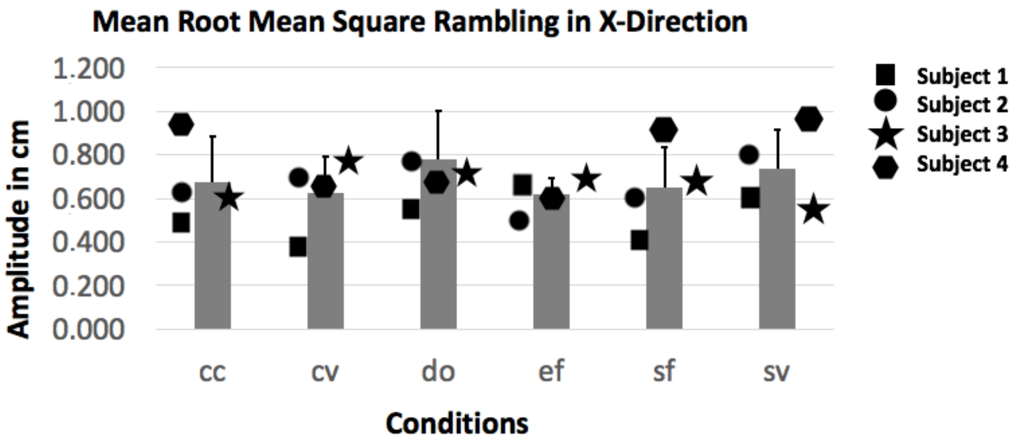

Figure 7.1: Mean RMS and SD of RM in x-direction for all conditions: control condition (cc), constant vibration (cv), device off (do), earth fixed (ef), sinusoidal force (sf) and sinusoidal vibration (sv).

From four averaged RMS of the subjects for rambling in x-direction, a mean value (MV) and the SD were determined. This was done for each of six conditions. The average amplitude for RM in x-direction for cc was 0.675±0.210 cm with the maximum at 0.975 cm (subject 4) and the minimum at 0.486 cm (subject 1). cv had a MV of 0.629±0.162 cm, maximum of 0.749 cm (subject 3) and minimum of 0.389 cm (subject 1). do shows a MV of 0.781±0.219 cm with a maximum of 1.082 cm (subject 4) and minimum of 0.564 cm (subject 1). ef had a MV of 0.619±0.078 cm, maximum of 0.688 cm (subject 3) and minimum of 0.512 cm (subject 2). sf a MV of 0.652±0.187 cm, maximum of 0.886 cm (subject 4), minimum of 0.437 cm (subject 1) and sv a MV of 0.736±0.179 cm, maximum of 0.961 cm (subject 4) and minimum of 0.570 cm (subject 3). All values are in table A.1 in the appendix.

The lowest amplitude and deviation shows ef condition which can be seen is figure 7.1. Trials with cv had the lowest amplitude of conditions wearing the haptic device. Without any haptic stimulus cc was not the condition with highest amplitude. This was do

which shows the highest SD as well. Except sv all conditions with a haptic stimulus had a lower mean amplitude of RM in x-direction than the conditions without a haptic stimulus.
For all conditions together QQ-plot for RM in x-direction in figure A16 top left in the appendix shows normality. Levene's test was not significant $F(5,18)=0.528$, $p=.752$ why I can assume homoscedasticity. Between haptic stimuli was no significant difference ($F(5,18)=0.513$, $p=.763$, $\eta^2=.125$) on RM in x-direction. All values are in table A.3 in the appendix.
Figure 7.1 shows that during the conditions subject 1 had the lowest amplitude except for ef and sv. For ef subject 2 had the lowest amplitude for RM in x-direction and for do the highest. Generally it was close to the MV. Subject 3 had the lowest value for sv and the highest for ef. Three times it was above and three times below average. Subject 4 had for cc, sf and sv the highest amplitude while being greater than SD. During do and ef it was below average. Detailed values are in table A.4 in the appendix.

## 7.3 Trembling In X-Direction

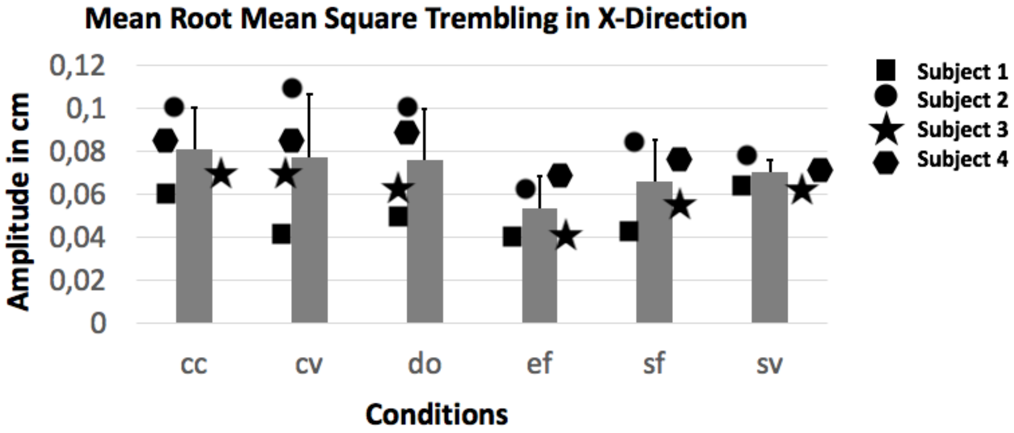

Figure 7.2: Mean RMS and SD of TM in x-direction for all conditions: control condition (cc), constant vibration (cv), device off (do), earth fixed (ef), sinusoidal force (sf) and sinusoidal vibration (sv).

The average amplitude for TM in x-direction for cc was 0.081±0.020 cm with the maximum at 0.106 cm (subject 2) and the minimum at 0.059 cm (subject 1). cv had a MV of 0.077±0.029 cm, maximum of 0.111 cm (subject 2) and minimum of 0.042 cm (subject 1). do shows a MV of 0.076±0.024 cm with a maximum of 0.100 cm (subject 2) and minimum of 0.049 cm (subject 1). ef had a MV of 0.053±0.015 cm, maximum of 0.070 cm (subject 4) and minimum of 0.040 cm (subject 1). sf a MV of 0.066±0.019 cm, maximum of 0.086 cm (subject 2) minimum of 0.044 cm (subject 1) and sv a MV of 0.070±0.006 cm, maximum of 0.078 cm (subject 2) and minimum of 0.065 cm (subject 3). All values are in table A.1

in the appendix.
Figure 7.2 shows ef had the lowest amplitude and second lowest SD. cc had the highest amplitude. sf and sv were the condition with lowest value of those with haptic stimulus of the wearable device and the second and third lowest of all. cv was slightly higher than do.
For all conditions together QQ-plot for TM in x-direction in figure A16 top right in the appendix shows normality. Levene's test was not significant $F(5,18)=2.145$, $p=.107$ why I can assume homoscedasticity. Between haptic stimuli was no significant difference ($F(5,18)=0.961$, $p=.467$, $\eta^2=.211$) on TM in x-direction. All values are in table A.3 in the appendix.
Figure 7.2 shows subject 1 with lowest amplitude for TM in x-direction for five conditions. During sv it had the second lowest value. Subject 2 had the highest amplitude except for ef with the second highest. Subject 3 hat the second lowest amplitude except for sv where it had the lowest. The fourth subject had the second highest amplitude except for ef with the highest. Detailed values are in table A.4 in the appendix.

## 7.4 Rambling In Y-Direction

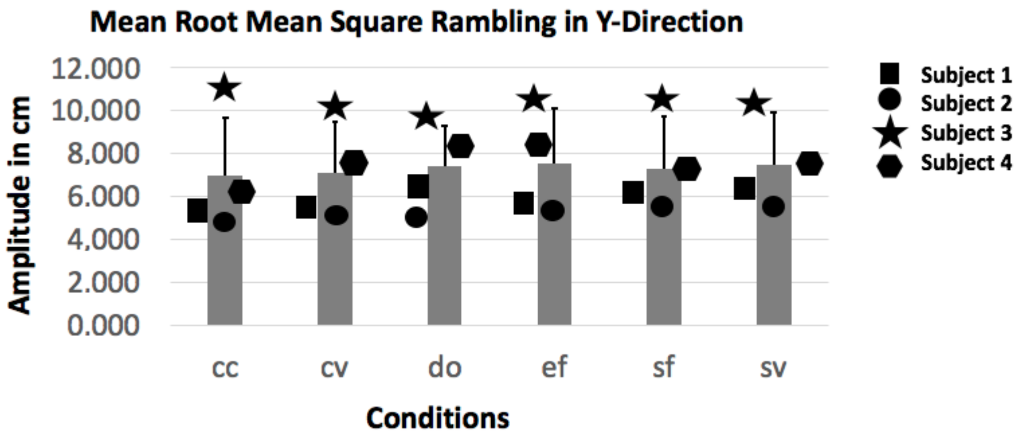

Figure 7.3: Mean RMS and SD of RM in y-direction for all conditions: control condition (cc), constant vibration (cv), device off (do), earth fixed (ef), sinusoidal force (sf) and sinusoidal vibration (sv).

From four averaged RMS of the subjects for rambling in y-direction, a MV and the SD were determined. This was done for each of six conditions. The average amplitude for RM in y-direction for cc was 6.995±2.682 cm with the maximum at 10.967 cm (subject 3) and the minimum at 5.194 cm (subject 2). cv had a MV of 7.108±2.399 cm, maximum of 10.306 cm (subject 3) and minimum of 4.928 cm (subject 2). do shows a MV of 7.410±1.926 cm with a maximum of 9.619 cm (subject 3) and minimum of 5.214 cm (subject 2). ef had a MV of 7.549±2.562 cm, maximum of 10.761 cm (subject 3) and minimum

of 5.308 cm (subject 2). sf a MV of 7.315±2.407 cm, maximum of 10.783 cm (subject 3) minimum of 5.340 cm (subject 2) and sv a MV of 7.509±2.415 cm, maximum of 10.861 cm and minimum of 5.294 cm. All values are in table A.1 in the appendix.
Condition of cc had the lowest amplitude followed by cv, cc had the highest SD as seen in figure 7.3. Conditions with haptic stimulus form the wearable device show the highest amplitude from sv and sf with the highest value. The deviations do not spread noticeable across conditions.
For all conditions together QQ-plot for RM in y-direction in figure A16 middle left in the appendix shows normality. Levene's test was not significant $F(5,18)=0.109$, $p=.989$ why I can assume homoscedasticity. Between haptic stimuli was no significant difference ($F(5,18)=0.034$, $p=.999$, $\eta^2=.009$) on RM in y-direction. All values are in table A.3 in the appendix.
Figure 7.3 shows a consistent ranking among subjects. Subject 2 had the lowest, subject 1 the second lowest, subject 4 the second highest and subject 3 the highest amplitude. Detailed values are in table A.4 in the appendix.

## 7.5 Trembling In Y-Direction

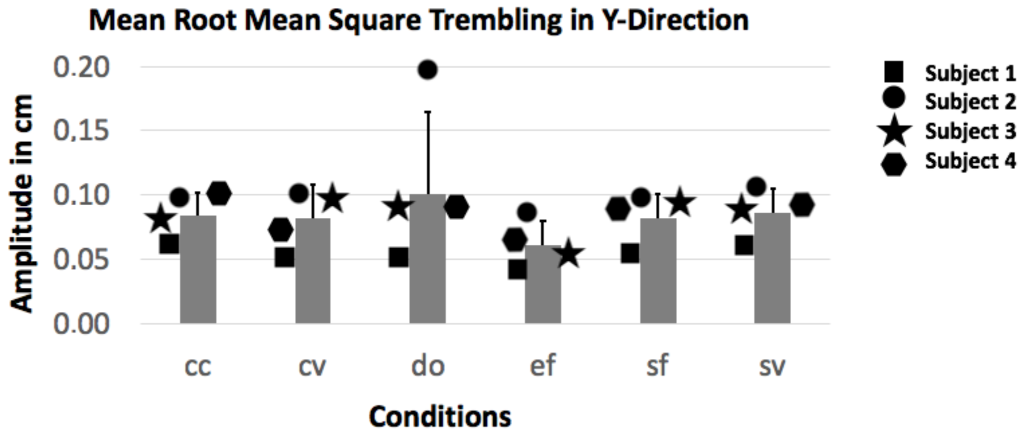

Figure 7.4: Mean RMS and SD of TM in y-direction for all conditions: control condition (cc), constant vibration (cv), device off (do), earth fixed (ef), sinusoidal force (sf) and sinusoidal vibration (sv).

The average amplitude for TM in y-direction for cc was 0.084±0.019 cm with the maximum at 0.102 cm (subject 4) and the minimum at 0.060 cm (subject 1). cv had a MV of 0.083±0.026 cm, maximum of 0.109 cm (subject 2) and minimum of 0.051 cm (subject 1). do shows a MV of 0.101±0.064 cm with a maximum of 0.194 cm (subject 2) and minimum of 0.051 cm (subject 1). ef had a MV of 0.061±0.019 cm, maximum of 0.086 cm (subject 2) and minimum of 0.040 cm (subject 1). sf a MV of 0.082±0.019 cm, maximum of 0.095 cm (subject 2) minimum of 0.054 cm (subject 1) and sv a MV of 0.086±0.019 cm, maximum

of 0.111 cm (subject 2) and minimum of 0.065 cm (subject 1). All values are in table A.1 in the appendix.
Condition of ef had the lowest amplitude as seen in figure 7.4. Two conditions of cv and sf were slightly lower than cc while sv was higher.do shows traceable the highest amplitude. Except for do which had the highest SD all deviations are the same with cv the second highest.
For all conditions together QQ-plot for TM in y-direction in figure A.16 middle right in the appendix shows normality. Levene's test was not significant $F(5,18)=2.501$, $p=.069$ why I can assume homoscedasticity. Between haptic stimuli was no significant difference ($F(5,18)=0.628$, $p=.681$, $\eta^2=.149$) on TM in x-direction. All values are in table A.3 in the appendix.
Subject 1 had the lowest amplitude during all conditions, as seen in figure 7.4. Subject 2 had the the highest value except for cc. Subject 3 had the second lowest for cc, do, sv and ef, for cv and sf the second highest. The fourth subject had the second highest amplitude during condition do, ef and sv. During sf and cv the second lowest and while cc the highest. Detailed values are in table A.4 in the appendix.

## 7.6 COP-Velocity

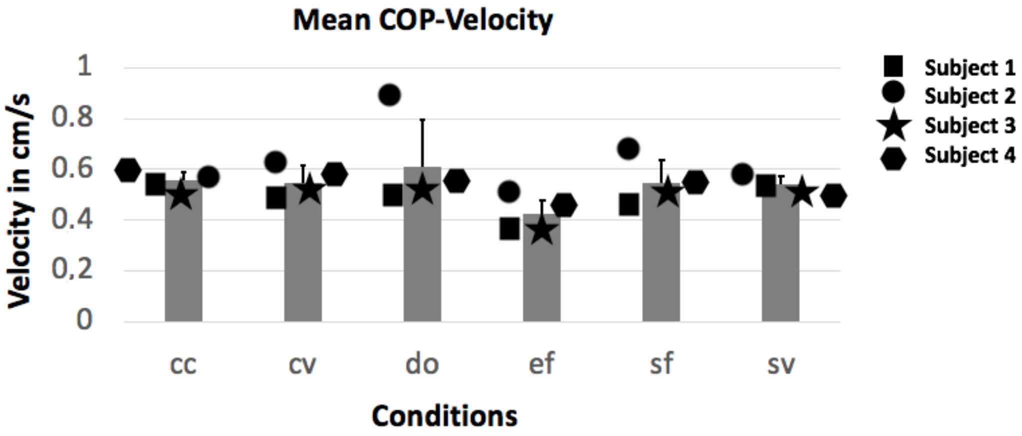

Figure 7.5: MV and SD of COP-velocity for all conditions: control condition (cc), constant vibration (cv), device off (do), earth fixed (ef), sinusoidal force (sf) and sinusoidal vibration (sv).

From the four averaged COP-velocity terms of the subjects, a MV and the SD were determined. This was done for each of six conditions. The average COP-velocity for cc was 0.555±0.031 cm/s with the maximum at 0.590 cm/s (subject 4) and the minimum at 0.515 cm/s (subject 3). cv had a MV of 0.548±0.067 cm/s, maximum of 0.625 cm/s (subject 2) and minimum of 0.475 cm/s (subject 1). do shows a MV of 0.612±0.184 cm/s with a maximum of 0.886 cm/s (subject 2) and minimum of 0.499 cm/s (subject 1). ef had a

MV of 0.425±0.053 cm/s, maximum of 0.494 cm/s (subject 2) and minimum of 0.381 cm/s (subject 3). sf a MV of 0.546±088 cm/s, maximum of 0.672 cm/s (subject 2) minimum of 0.475 cm/s (subject 1) and sv a MV of 0.539±0.033 cm/s, maximum of 0.584 cm/s (subject 2) and minimum of 0.505 cm/s (subject 4). All values are in table A.1 in the appendix.
Figure 7.5 shows the lowest COP-velocity for ef. sf, cv and sv as conditions with haptic stimulus form the wearable device had higher velocities. do followed by cc had the highest COP-velocity. Except for do which had the highest SD all other deviations are similar with the lowest for cc followed nearby sv.
For all conditions together QQ-plot for COP-velocity in figure A16 bottom left in the appendix shows normality. Levene's test was significant $F(5,18)=3.376$, $p=.025$ why I can not assume homoscedasticity. Friedman-Test showed no significant difference between haptic stimuli ($x^2(5)=10.429$, $p=.064$) on COP-velocity.
For condition cv, do and sf subject 1 had the lowest COP-velocity as seen in figure 7.5. For cc and ef it had the second lowest while for sv the second highest. Subject 2 had the highest value for all conditions except cc where it had the second highest. The third subject had the lowest value for cc and ef, the second lowest for cv, do, sf and sv. The fourth subject had the highest velocity during condition cc and the lowest during sv. During all other conditions subject 3 had the second highest. Detailed values are in table A.4 in the appendix.

## 7.7 Subjects individual

Different haptic stimuli did not show significant differences for different parameters across subjects. Therefore I examined subjects individually to see if there was an effect.

Table 7.2: *ANOVA and Friedman-test after Bonferroni correction for each subject and parameter.*

| Subject | Value | RM x | TM x | RM y | TM y | COP-velocity |
|---|---|---|---|---|---|---|
| 1 | F-value/Chi$^2$ | 5.810 | 3.480 | 5.361 | 14.762 | 14.667 |
| | p-value | .325 | .054 | .005 | .046 | .048 |
| 2 | F-value/Chi$^2$ | 4.191 | 1.915 | 0.845 | 1.803 | 12.762 |
| | p-value | .522 | .121 | .529 | .142 | .026 |
| 3 | F-value/Chi$^2$ | 3.333 | 4.139 | 8.095 | 6.857 | 12.880 |
| | p-value | .649 | .011 | .151 | .232 | >.001 |
| 4 | F-value/Chi$^2$ | 5.905 | 1.348 | 10.260 | 8.095 | 5.558 |
| | p-value | .316 | .272 | >.001 | .151 | .002 |

### Subject 1

Test for homoscedasticity was significant ($F$(5,30=3.548), $p$=.012) for RM in x-direction, TM in y-direction ($F$(5,30)=5.048, $p$=.002) and COP-velocity ($F$(5,30=2.699), $p$=.040). Consequently homoscedasticity is not given. For TM in x-direction ($F$(5,30=1.585), $p$=.194) and RM in y-direction ($F$(5,30=1.053), $p$=.406) Levene's-test was not significant and we can assume homoscedasticity. Values can be seen in table A.5 in the appendix. All QQ-plots form figure A17 in the appendix show normality. ANOVA for TM in x-direction showed no significant difference after post hoc Bonferroni correction ($F$(5,30=3.480), $p$=.054) between conditions and a significant difference for RM in y-direction ($F$(5,30= 5.361), $p$=.005). Friedman-Test for RM in x-direction was not significant ($x^2$(5,30)=5.810, $p$=.325). Friedman-Test for TM in y-direction ($x^2$(5,30)=14.762, $p$=.046) and COP-velocity ($x^2$(5,30) =14.667, $p$=.048) showed a significant difference between conditions. All values can be seen in table 7.2. Post hoc analysis for RM in y-direction of Tukey's showed significant differences for pairs of do-cc (p=.011), sv-cc (p=.030), do-cv (p=.021) and ef-do (p=.023). Values can be seen in table A.10 in the appendix. Games-Howell post hoc test for TM in y-direction was significant for cc-ef (p=.020) and sf-do (p=.030) and for COP-velocity for pairs of cc-ef (p<.001), cv-ef (p=.021) and do-ef (p=.019). All values can be seen in table A.11 in the appendix.

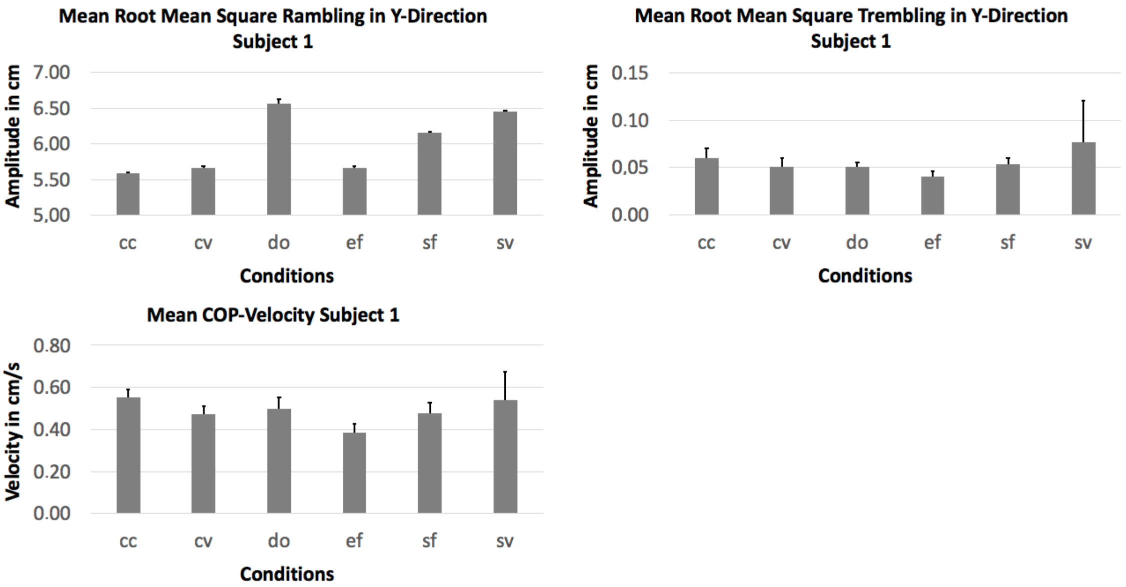

Figure 7.6: Mean values for RM in y-direction, TM in y-direction and COP-velocity of subject 1. Plot **top left** shows mean amplitude for RM in y-direction for subject 1 over all conditions. Plot **top right** shows mean amplitude for RM in y-direction for subject 1 over all conditions. Plot **bottom left** shows mean COP-velocity for subject 1 over all conditions.

Plot top left in figure 7.7 demonstrates the differences within conditions of RM in y-direction. Condition do 6.560±0.418 cm (max=7.009 cm, min=5.977 cm), sv 6.448±0.729

cm (max=7.494 cm, min=5.315 cm) and sf 6.155±0.380 cm (max=6.608 cm, min=5.552 cm) had relatively high and cc 5.590±0.312 cm (max=5.958 cm, min=5.032 cm), cv 5.659±0.438 cm (max=6.306 cm, min=4.935 cm) and ef 5.669±0.331 cm (max=6.010 cm, min=5.158 cm) low MV. cv had the lowest amplitude among stimuli of the haptic device while sv and sf had the third and second highest amplitude. Plot top right in figure 7.7 shows the mean amplitude for TM in y-direction. ef 0.040±0.006 cm (max=0.045 cm min=0.032 cm) had the lowest MV followed by do 0.051±0.005 cm (max=0.058 cm, min=0.046 cm) and cv 0.051±0.009 cm (max=0.066 cm, min=0.043 cm). sf 0.054±0.006 cm (max=0.064 cm, min=0.046 cm) and cc 0.060±0.010 cm (max=0.072 cm, min=0.047 cm) were higher while sv 0.077±0.044 cm (max=0.160 cm, min=0.040 cm) had the highest amplitude. Plot bottom left in figure 7.7 visualizes ef 0.386±0.040 cm/s (max=0.446 cm/s, min=0.330 cm/s) as the lowest MV for COP-velocity followed by cv 0.475±0.034 cm/s (max=0.509 cm/s, min=0.429 cm/s) and sv 0.475±0.054 cm/s (max=0.542 cm/s, min=0.380 cm/s). Conditions of do 0.499±0.053 cm/s (max=0.582 cm/s, min=0.436 cm/s), sv 0.540±0.134 cm/s (max= 0.777 cm/s, min=0.398 cm/s) and cc 0.551±0.041 cm/s (max=0.588 cm/s, min=0.477 cm/s) had the highest amplitude. All values can be seen in table A.6 in the appendix.

**Subject 2**

Test for homoscedasticity was significant ($F$(5,30=2.649), $p$=.043) for RM in x-direction and COP-velocity ($F$(5,30)=11.706, $p$=<.001). Consequently homoscedasticity is not given. For TM in x-direction ($F$(5,30=1.760), $p$=.152), RM in y-direction ($F$(5,30=0.655), $p$=.660) and TM in y-direction ($F$(5,30=0.655), $p$=.660) Levene's-test was not significant and we can assume homoscedasticity. Values can be seen in table A.5 in the appendix. All QQ-plots form figure A18 in the appendix show normality. After post hoc Bonferroni correction Friedman-Test was significant ($x^2$(5,30)=12.762, $p$=.023) for COP-velocity. For RM in x-direction Friedman-Test was not significant ($x^2$(5,30)=4.191, $p$=.522). ANOVA showed no significant differences for TM in x-direction ($F$(5,30=1.915), $p$=.121), RM in y-direction ($F$(5,30=0.845), $p$=.529) and TM in y-direction ($F$(5,30=1.803), $p$=.142) All values can be seen in table 7.2. Post hoc analysis of Games-Howell resulted in a difference of conditions for ef-do (p=.041).

Figure 7.7 shows condition of ef 0.494±0.065 cm/s (max=0.579 cm/s, min=0.414 cm/s) had the lowest mean velocity followed by cc 0.566±0.052 cm/s (max=0.630 cm/s, min=0.502 cm/s) sv 0.584±0.115 cm/s (max=0.777 cm/s, min=0.478 cm/s). Condition of do 0.886± 0.421 cm/s (max=1.489 cm/s, min=0.542 cm/s) had the highest velocity with sf 0.672± 0.197 cm/s (max =1.054 cm/s, min=0.519 cm/s) in second and cv 0.611±0.040 cm/s (max= 0.657 cm/s, min=0.542 cm/s) in third. All values are in table A.7 in the appendix.

**Subject 3**

Test for homoscedasticity was significant ($F$(5,30=2.850), $p$=.032) for RM in x-direction, RM ($F$(5,30)=3.780, $p$=<.009) and TM in y-direction ($F$(5,30)=4.954, $p$=<.002). Consequently homoscedasticity is not given. For TM in x-direction ($F$(5,30=0.300), $p$=.909) and COP-velocity ($F$(5,30=1.370), $p$=.264) Levene's-test was not significant and we can

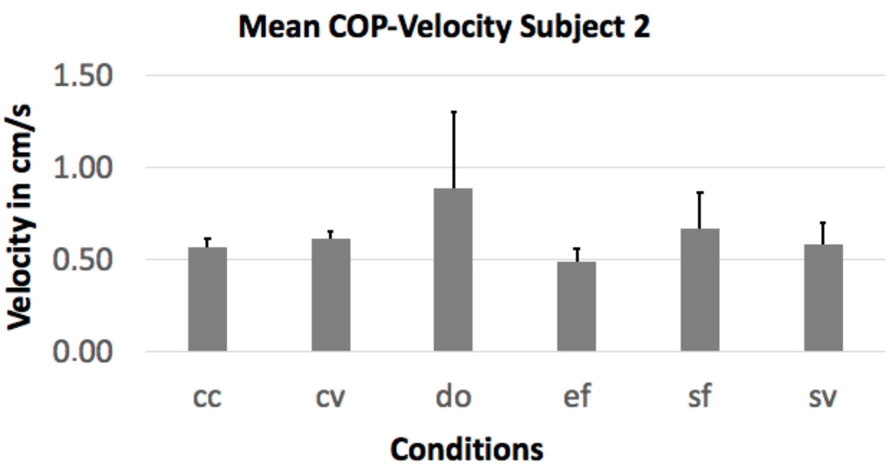

Figure 7.7: Mean values for all conditions of COP-velocity of subject 2.

assume homoscedasticity. Values are in table A.5 in the appendix. QQ-plots show normality with outliners for all parameters except for RM and TM in y-direction in plot middle left and middle right in figure A19 in the appendix. After post hoc Bonferroni correction ANOVA was significant for TM in x-direction (*F*(5,30=4.139), *p*=.011) and COP-velocity (*F*(5,30=12.880), *p*<.001). All values are in table 7.2. Post hoc analysis for RM in x-direction of Tukey's showed significant differences for pairs of ef-cc (p=.004) and ef-cv (p=.019). Analysis of Tukey's for COP-velocity was significant for pairs of ef-cc (p<.001), ef-cv (p<.001), ef-do (p<.001), sf-ef (p<.001) and sv-ef (p<.001). All values can be seen in table A.12 in the appendix.

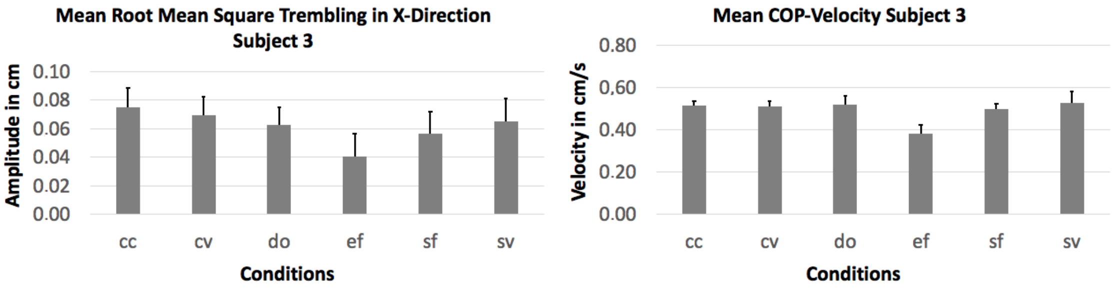

Figure 7.8: Mean values for TM in x-direction and COP-velocity of subject 2. Plot **left** shows mean amplitude for RM in x-direction for subject 3 over all conditions. Plot **right** shows mean COP-velocity for subject 3 over all conditions.

Plot left in figure 7.7 visualizes differences within conditions of TM in x-direction for subject 3. Condition ef had the lowest amplitude of 0.040±0.016 cm (max=0.067 cm, min=0.023 cm) followed by sf of 0.056±0.016 cm (max=0.079 cm, min=0.039 cm) and do with 0.063±0.012 cm (max=0.074 cm, min=0.042 cm). Condition of cc had the highest amplitude of TM in x-direction with 0.075±0.014 cm (max=0.099 cm, min=0.062 cm), cv the second highest of 0.069±0.013 cm (max=0.091 cm, min=0.054 cm) and sv the third highest of 0.065±0.016 cm (max=0.092 cm, min=0.051 cm). Right plot in figure 7.7 shows mean COP-velocity for subject 3. Condition of ef was the slowest with a velocity of 0.381±0.041 cm/s (max=0.431 cm/s, min=0.330 cm/s) followed by sf with 0.500± 0.024 cm/s (max=0.537 cm/s, min=0.476 cm/s) and cv with 0.513±0.026 cm/s (max=0.549 cm/s, min= 0.483 cm/s). Condition of sv had the highest velocity of 0.527±0.056 cm/s (max= 0.635 cm/s, min= 0.492 cm/s) followed by do of 0.519±0.043 cm/s (max=0.581 cm/s, min= 0.461 cm/s) and cc of 0.515±0.023 cm/s (max=0.555 cm/s, min=0.492 cm/s).

**Subject 4**

Test for homoscedasticity was significant ($F(5,30=4.302)$, $p=.005$) for RM in x-direction and TM in y-direction ($F(5,30=3.472)$, $p=.014$). Consequently homoscedasticity is not given. For TM in x-direction ($F(5,30=1.037)$, $p=.414$), RM in y-direction ($F(5,30=0.298)$, $p=.910$) and COP-velocity ($F(5,30=1.427)$, $p=.243$) Levene's-test was not significant and we can assume homoscedasticity. Values are in table A.5 in the appendix. All QQ-plots form figure A20 in the appendix show normality. After Bonferroni correction ANOVA for RM in y-direction ($F(5,30=10.260)$, $p<.001$) and COP-velocity ($F(5,30=5.558)$, $p0.002$) was significant. ANOVA for TM in x-direction ($F(5,30=1.348)$, $p=.272$) and Friedman-Test for RM in x-direction ($x^2(5,30)=5.905$, $p=.316$) and TM in y-direction ($x^2(5,30)=8.095$, $p=.151$) were not significant. All values can be seen in table 7.2.
Post-hoc analysis for RM in y-direction showed significant differences between the pairings of cv-cc (p=.013), do-cc (p=<.001), ef-cc (p=<.001), sv-cc (p=.013), sf-do (p=.017) and sf-ef (p=.004). For COP-velocity the pairings of ef-cc (p=.001), ef-cv (p=.002) and ef-do (p=.043) were significant. All values can be seen in table A.13 in the appendix.

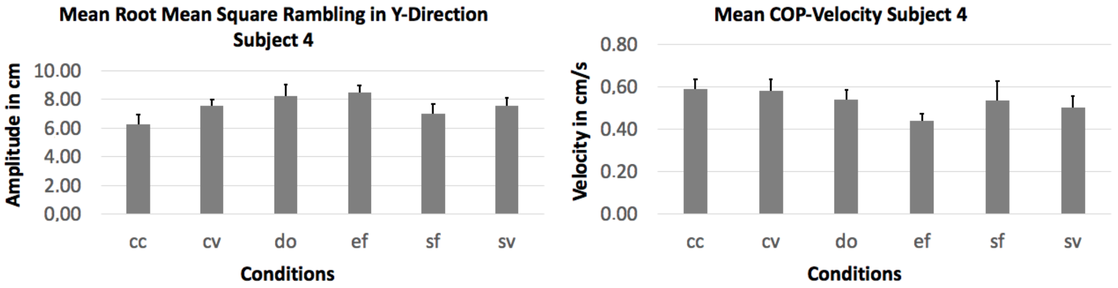

Figure 7.9: Mean values for RM in y-direction and COP-velocity of subject 3. Plot **left** shows mean amplitude for TM in y-direction for subject 4 over all conditions. Plot **right** shows mean COP-velocity for subject 4 over all conditions.

Left plot in figure 7.7 visualizes mean amplitude for RM in y-direction for subject 4. Condition cc had the lowest amplitude of 6.228±0.715 cm (max=7.261 cm, min=5.216 cm) followed by sf of 6.983±0.666 cm (max=8.001 cm, min=6.050 cm) and sv with 7.533±0.582 cm (max=8.197 cm, min=6.594 cm). The highest mean amplitude had ef with 8.458±0.498 cm (max=9.238 cm, min=7.682 cm), the second highest had do of 8.248±0.789 cm (max= 9.686

cm, min=7.383 cm) and the third highest had cv of 7.538±0.446 cm (max=8.314 cm, min= 7.097 cm). Right plot in figure 7.7 shows mean COP-velocity of subject 4. Condition ef had the lowest velocity of 0.440±0.035 cm/s (max=0.498 cm/s, min=0.406 cm/s) followed by sv with 0.505±0.051 cm/s (max=0.442 cm/s, min=0.442 cm/s) and sf of 0.537±0.091 cm/s (max= 0.692 cm/s, min=0.455 cm/s). Condition cc had the highest velocity of 0.590± 0.049 cm/s (max=0.637 cm/s, min=0.502 cm/s), cv the second highest of 0.581±0.056 cm/s (max=0.643 cm/s, min= 0.481 cm/s) and do the third highest of 0.542±0.045 cm/s (max= 0.604 cm/s, min=0.482 cm/s). All values can be seen in table A.9 in the appendix.

# Chapter 8

# Discussion

In the present study, the influence of a light touch cue by a wearable device on the postural sway was investigated. In the following I will discuss Subsequently, the research questions and the hypotheses from section 4.1 are discussed.
In order to provide an overview of the most important interpretations, noteworthy findings are listed below:

1. There is no significant effect of a light touch cue by the haptic device or an earth fixed reference point at the wrist on the sway parameters rambling and trembling in x and y-direction and COP-velocity. But an earth fixed reference point of light touch at the wrist tends to have a reducing effect on rambling in x-direction, trembling in x and y-direction and COP-velocity.
2. Individual analysis of each subjects shows a significant effect on COP-velocity with mostly the condition of an earth fixed reference point as the causing effect.

Since neither the ANOVA nor the Friedman-Test show significant differences for the results of the overall subjects, the following assumptions can be made for these results: (1) An earth fixed reference point for light touch on the wrist does not have a significant effect on postural sway. (2) A light touch stimulus provided by a wearable device does not have a significant effect on postural sway.
Due to the non-significant results, the hypotheses (see section 4.1) that (1) light touch cue of an earth fixed reference point at the wrist has a reducing effect on body sway, (2) light touch cue of a wearable device has a reducing effect on body sway and (3) different haptic light touch cues of a wearable device have a reducing effect on body sway are rejected.

## 8.1 Earth Fixed Reference Point

In order to answer the research questions and hypotheses, I will first discuss the effect of the earth fixed reference point. The results will by discussed in chronological order.

The statistical calculations of ANOVA did not show any significant difference for all five parameters, although the descriptive analysis suggests an effect. The non-significant result contradicts the findings of Wasling et al. [WNGO05], which showed a reduction of path length and sway amplitude, which is comparable to RM because of its dependency on $COP_x$, by a light touch to the skin of the distal forearm 2 cm proximal of the ulnar styloid process (see fig. 3.2). Although the light touch was not performed at the same spot on the forearm as in this work, approximately 2 cm proximally in the middle of the wrist on the dorsal side (see fig. 6.2 (3)), the positions are very close together. The texture of the skin should be very similar at both spots. The results of Rabin et al. [RBDL99] may provide an explanation. It is important in which plane to the stronger sway direction the reference point is located, because the somatosensory cues from the fingertip provide both directional and amplitude information about the sway when the finger touches a surface in the unstable plane. If the reference point is located on the lateral side when the swing in AP direction is stronger, it has less effect than when it is in the frontal plane. In this work the sway amplitude in AP and ML direction were not compared. Since the subjects were in a bipedal Romberg's stance, it can be assumed that the stronger sway is in the AP direction. In a tandem Romberg's stance this would probably be the ML direction. However, this interpretation should also be considered with caution, as in the study by Rabin et al. [RBDL99] the fingertip was the contact point and in this study the transition from the dorsal wrist to the forearm. Glabrous skin at the fingertip has a much higher density of subcutaneous mechanoreceptors and the postural position of the arm including the hand is much different from the normal upright stance. In addition, Biggs and Srinivasan [BS02] have investigated the sensitivity at the forearm to tangential and vertical forces. They concluded that the subjects at the forearm are more sensitive to tangential forces than to vertical forces. From the literature, no answer can be deduced in which direction the earth fixed reference point should have been positioned in order to create the greatest possible effect. This could only be achieved by evaluating data. However, in the measurement of this study the position of the earth fixed reference point in lateral direction had the great advantage that the subjects could take the most natural and relaxed neutral posture. Both for the condition of the earth fixed reference point and while wearing the wearable device. Furthermore, the conditions could be compared particularly well in this way, as the posture of the subjects did not change.

The inconsistency of sensitivity and force direction raises the question whether the light touch cue from the earth fixed reference point was even sufficient. During the measurement, the force exerted by the contact point on the forearm with the force sensor was not measured and controlled. It is therefore possible that during the measurement the contact force was much lower or higher than the force defined for the light touch of <1 N. However, too much force should also have had an effect on the body sway. The tests by Jeka and Lackner [JR94] showed a reduction in postural sway of 60% with a contact force through the fingertips of 5-8 N. However, a contact force lower than 1 N should also have had a reducing effect on postural sway. Thus, for a force of approximately 0.2 N of the fingertip, more than 90% of direction of motion was correctly identified [ibid.]. In addition, all subjects in the work of Jeka and Lackner made a contact of 0.4 N with the fingertip, even though they were allowed up to 1 N of force. This value is in consistent with the maximal afferent activity observed at approximately 0.3-0.5 N [WJ87].

Now the question arises whether the cutaneous receptors at the forearm transmit sufficient sensory information about the contact with the earth fixed reference point. Jeka and Lackner [JEBL96] stated, when haptic cues are functionally meaningful for the task, sensory information can be as effective as physical support in stabilizing upright stance. The fast adapting (FA) receptors at the forearm include both the Pacinian corpuscles and Root hair plexus, which are very sensitive to vibration and movement between the skin and a contact point and sensitive to light touch [JH92]. Even the discharge of a single Pacinian corpuscle results in the perception of a touch, as the receptors are individually very sensitive [ibid.]. The typical discharge rates of fast adapting (FA) receptors are between 10-300 Hz [ibid.], which is much higher than the mean body sway of 0.3 Hz [ZK98]. Besides the FA-fibre types, hairy skin also contains slowly adapting (SA) receptors of Merkel cells and Ruffini corpuscles. These react to pressure and have a significantly lower discharge rate at 0.3-3 Hz [MWN$^+$09]. It can therefore be assumed that only SA receptors contribute to light touch. Jeka and Lackner [JL95] showed that when the fingertip touches a smooth surface and slips off, it generates pressure and when it does not slip off, it generates a shear force. Each individual situation would have created a different profile of afferents. Rogers et al. [RWLF01] created the contact point with the soft side of a Velcro. This stimulus would have produced a different profile than those listed by Jeka and Lackner, suggesting that no single type of mechanoreceptor is responsible for the postural actions.
Jeka and Lackner [JR94] assume that, in addition to finger contact, the position of the limbs and their control to obtain the light touch cue plays an important role. It is possible that the subject has access to further information from the periphery through fine movements of the arm. A similar conclusion can be drawn from the results of this study. The subjects were instructed to maintain contact with the ef reference point at the wrist. However, this task was relieved from them to a considerable extent, as the reference point was placed so close to the body with the tripod that even standing upright without an active contact movement provided a slight contact. This state for ef was required to reach the most comparable position for the relaxed standing when wearing the wearable device and during control condition. How much effort the individual subjects had to make to maintain contact was not recorded, but this loss of information could have led to the non-significant result. This statement is contradicted by the results of Rogers et al. [RWLF01]. In their study, body sway was reduced without such information about limbs position. One reason for this could be that CNS prefers to obtain information from the periphery to assess movement [ibid.] Motor commands from the CNS play a rather minor role [ibid.]. However, this cannot be regarded as a grounded analysis.
Even if the results are not significant for all subjects, it is noticeable that for four of five parameters analysed, RM in x-direction and TM in x (ML) and y-direction (AP) as well as COP-velocity, the condition with the ef reference point had the lowest amplitude or velocity. The mean reduction of sway amplitude for ef was 8.3%. It is interesting that

for two subjects ef had the higher amplitude than cc. It is noticeable that these are the subjects with the two lowest amplitudes for cc, especially since subject 1 is clearly below the respective mean value in all other conditions. A possible cause for this could be that subject 1 and 3 are non-responders and react weakly to the light touch cue or in this case do not react at all.

Since RM is derived from the trajectory of the COP in the respective direction in ML or AP (see section 2.2.2) it can be assumed that the control of the reference point towards the IEP takes place supra-spinally. This conclusion is based on the results of Lackner et al. [LRD00], which show that the reduction of postural sway by light touch is, compared to the cue, approximately 250 ms delayed in the movement of the COP. All subcutaneous mechanoreceptors are connected to the brain and the corresponding processing area via the fast, myelinated A$\beta$ fibre types (see tab. 2.1). In somatosensory cortex afferent nerve fibres are displayed in a somatotopic arrangement [Ill08]. After the afferent information from the periphery arrives in CNS, a switch to efferent pathways leading to the effectors and finally their movement execution [HG06] takes place.

The statistical inference analysis of ANOVA did not show a significant difference between the conditions for the parameter TM in x-direction ($F(5{,}18)=0.961$, $p=.467$, $\eta^2=.211$). Descriptively, however, it is noticeable that, as before for RM, the condition of the ef in x-direction has a lower mean amplitude. This is an average difference of 0.028 cm and corresponds to a reduction in amplitude of 34.6%. It is interesting to note that the percentage decrease of the amplitude of TM compared to that of RM is much more significant with only 8.3%. This contradicts the findings of Santos et al. [dSPRA$^+$19], which show a reduction of amplitude of RM by light touch of 38.5±3.2% and TM of 18.5±5.4%. In this case, it should be noted that Santos et al. were concerned with light touch through the finger tip. This may explain the differences.
The fact that the TM amplitude was also so low was also confirmed by Santos et al. [dSPRA$^+$19]. They found the reason for the low TM amplitude to be that, although the COP-velocity was low, the TM amplitude was low. The reasoning is plausible, since a general decrease in COP-velocity also reduces the $\mathrm{COP_x}$ and thus the difference between RM and the $\mathrm{COP_x}$. Although muscle activity was not analysed in this study, it is possible the selected strategy of active and passive postural control (see subsection 3.2.1) may not be associated with the increased muscle co-activation or higher joint apparent stiffness as, in such conditions, the amplitude of TM should increase leading to reduced postural stability.

As described in subsection 2.1.3, the body works with different systems during motor control. As previously described, RM is also assigned to supra spinal information processing due to the time delay. Since TM is the difference between COP and RM, it does not show any time delay on the reference parameters. Zatsiorsky and Duarte [ZD99, ZD02], who made the discovery of the two parameters RM and TM public, assume that spinal reflexes are behind the TM trajectory. Via the dermatome C6 (see fig.

A.2 in the appendix), in addition to the skin area at the forearm where the contact point was also at the wrist, both the index finger and thumb of each hand are innervated by the same afferents [PKS14]. Among other things, this segmental synaptic interconnection of the mechanoreceptive and proprioceptive afferents serves to control spinal reflexes. From this it can be concluded that a light touch at the fingertip as well as at the dorsal wrist is innervated by the same neurons. This means that sensory information from the fingertip for spinal reflexes are processed in the same way as those at the wrist. Both body parts can be compared for the effect of light touch.
For the hypothesis that TM are reflex-like reactions, Santos et al. [dSPRA⁺19] and Sarabon et al. [SPL13] are critical and consider the statement to be too simplistic, but have no proof of this. It is obvious, however, that TM and also RM belong to the control system feedback control (see subsection 2.2.3). With RM in x-direction a heterogeneous picture was shown when comparing individual subjects, since two subjects had a lower mean amplitude during cc compared to that of ef. This is not the case for TM. The subjects that are also below the mean value at cc do so also for the condition ef and each have a lower amplitude during the condition ef compared to cc. None of the subjects represents an outlier that either goes down or up. According to this, for subject 1 and 3 for TM had a reducing effect, but not for RM. One possibility could be that the haptic stimulus was sufficient for spinal reflexes.

Before discussing the result for rambling in y-direction, I would like to point out a peculiarity. The absolute values of the amplitude are unusually high. This has to do with a property of the measured data of the force plate and its post processing. The mean value of all subjects is therefore distorted and does not allow any interpretation. However, for individual subjects the distortion has no effect. For a more detailed explanation of the problem please refer to subsection „Limitations“ 8.3.

The statistical inference analysis of ANOVA did not show a significant difference between the conditions for the parameter RM in y-direction ($F(5,18)=0.034$, $p=.999$, $\eta^2=.009$). Within the subjects there are no differences between ranks. Thus subject 2 followed by subject 1, 4 and 3 showed the highest amplitude for both conditions. Only for subject 3, which had the highest amplitude for both conditions, there was an reducing effect for. As an explanation the statement of Rabin et al. [RBDL99], that the earth fixed reference point in the lateral plane has a weaker effect to the stronger sway direction than when it is in the frontal plane. This was, as already mentioned, not evaluated and it must be assumed that the y-direction was the stronger sway direction due to the bipedal Romberg's stance.

The statistical inference analysis of ANOVA did not show a significant difference between the conditions for the parameter TM in y-direction ($F(5,18)=0.628$, $p=.681$, $\eta^2=.149$). Despite the non-significant result, the descriptive analysis shows a difference between the conditions cc and ef. The reduction of 0.023 cm by an earth fixed reference point, which represents a decrease of 27.4% is quiet remarkable. This result is interesting because the earth fixed reference point shows a reducing effect on TM in y-direction, but not for RM in y-direction. In x-direction, an effect has been shown for both parameters. As mentioned before, TM probably belongs to the control system feedback control. The feedback control system can be differentiated into different strategies [Hor06]. In one strategy, the balance in human upright stance is mainly maintained by ankle movement (plantar/dorsiflexor), which according to Winter et al. controls the AP direction (y-direction) in a bipedal stance [WPP$^{+}$98]. In the second strategy, lower trunk, pelvic and hip (abductor/adductor) muscles are activated, which is the control of the ML direction (x-direction) [ibid.]. No muscle activity was investigated by EMG in this study. But referring again to the statement of Rabin et al. [RBDL99], if the reference point is in the frontal plane of sway direction, a stronger effect results. For comparison, for TM in x-direction, the frontal plane, the reduction was in total 0.028 cm and relatively 34.6% and for y-direction, the lateral plane, reduction was in total only 0.023 cm and relatively 27.4%. This supports the statement of Rabin et al. that the frontal sway direction has a greater effect.

The statistical inference analysis of Friedman-Test did not show a significant difference between the conditions for the parameter COP-velocity ($x^2$(5)=10.429, $p$=.064). Compared to the other parameters the result is close to the level of significance (p=0.05). Descriptive analysis underlines, as for three out of four parameters before, a reduction of mean COP-velocity for condition ef compared to cc. COP-velocity is calculated from the distance between two COP-coordinates over time, which consist of the two COP$_x$ and COP$_y$-coordinates (see subsection 6.4). This mathematical dependence of COP-velocity on both RM and TM in x and y-direction would probably already indicate a reducing effect of ef. Accordingly, the same assumptions apply as for RM and TM in x and y-direction. The decreasing effects of RM in x-direction and TM in x and y-direction will probably have exceeded the increasing effect of RM in y-direction.

The analysis of individual subjects supports the interpretation of the descriptive analysis from the previous paragraphs. Although significant differences between ef and cc were found for only three out of four subjects, these results confirm the descriptive tendency towards a reducing effect of an earth fixed reference point on the wrist. It is possible that subjects 1 and 3 are non-responders to the results of the other two subjects due to the difference in amplitude of RM in x-direction. Another reason for this could be caused by the procedure, because it is noticeable that subject 1 and 3 of all subjects show an opposite effect. For preparation of procedure all conditions were randomised in advance. Only two conditions in which no haptic device was worn were placed alternately in first or last place for each subject for logistical reasons. For subject 1 and 3 the condition ef was placed last. Since the preparation procedure was the same for all subjects, subjects 1 and 3 had considerably more time between the trial with the force sensor Nano17 than subjects 2 and 4, which were measured directly after the test trial with the condition ef. This time lag could have had an influence on the remembered intensity of the light touch contact the subjects had to maintain. Contrary to this assumption, as mentioned before, the results of Jeka and Lackner [JR94] showed that contact with a force of 0.4 N or 5-8 N had a reducing effect on postural sway.

Although the inferential statistical analysis for overall subjects did not produce any significant results, the descriptive analysis in particular points to an effect caused by the earth fixed reference point. This is confirmed by significant results for individual subjects. Very likely for the non-significant results is the small sample size (n=4), which is due to the compliance with actions to reduce the risk of infection during the COVID-19 pandemic. If the thesis were to be put forward that the earth fixed reference point on the wrist has no effect on the body sway, a large part of the current literature would be questioned. Individual subjects show no reducing effect for some parameters. For other parameters, however, they all show a reducing effect. Especially the fact that all subjects show a decrease of the COP-velocity indicates an effect of the earth fixed reference point, because it can be seen as a kind of global parameter compared to RM and TM in x and y-direction. The reason for the increase of the amplitude of the parameter RM in y-direction should be clarified. On the basis of the results in this thesis only conjectures can be made. Conclusions about this effect can be drawn by the force and torque sensor measuring the forces and their directions at the earth fixed reference point. Unfortunately, for technical reasons, these could not be determined in this work.

Although for every parameter with the exception of RM in y-direction the condition with the earth fixed reference point showed lower values and even showed a significant difference for some subjects, the first research question, whether there is a light touch effect with an external fixed object at the wrist, is negated due to the non-significant results and the null hypothesis is maintained. Nevertheless, the descriptive analyses show a clear tendency towards an effect.

## 8.2 Wearable Haptic Device

After having previously answered the first research question in the subsection above, the following paragraphs deal with the second research question whether a wearable device at the wrist can effect body sway, and whether this effect is as effective as with an earth fixed object as well as the third research question whether the effect of the haptic device is different among three different stimuli conditions.

During the measurements, in addition to the already compared control condition (cc) and earth fixed reference point (ef), another condition without haptic stimulus was measured by the wearable haptic device. In the condition do, the wearable device was worn, but it did not execute an active light touch cue. The statistical analysis of ANOVA did not show any significant differences for the parameter RM in x-direction ($F(5,18)=0.513$, $p=.763$, $\eta^2=.125$). Descriptively, however, it is striking that do has the highest mean amplitude. Assuming that the haptic stimuli of the wearable device have a reducing effect, the results are not entirely clear. That the condition do had such an increase compared to the other conditions is unexpected. A possible explanation is that the subjects were disturbed in their equilibrium by the device. This disturbance variable cannot be completely eliminated, but the risk of distraction by the device through the setup was very low. In addition, all subjects stated that the device does not influence the balance. From an objective point of view, wearing the wearable device should even have had a reducing effect, as it was connected to earth via cable and the light forces could theoretically give feedback.

The fact that the condition cv showed a reducing effect is very interesting, because all four subjects after this condition made the statement by themselves that the vibration had a calming effect. During cv the constant pressure of $<1$N activated the slowly adapting (SA) Merkel cell and Ruffini corpuscle and the constant vibration activated the fast adapting (FA) Root hair plexus and Pacinian corpuscle. This results in more information through different mechanoreceptors and could explain the difference between cv and sf. However, this assumption is not supported by the literature, as the influence could not be clearly differentiated by the number and type of stimulus.
The fact that the condition sf did not have a stronger effect could again refer to the statement by Rabin et at. [RBDL99] that the light touch has a greater effect in the frontal plane of the stronger sway direction. By the position of the upright stance with arms hanging down relaxed, the force of the wearable device came from the lateral direction. That sv had an increase of the sway amplitude is not to clarify. Perhaps this stimulus, contrary to the cv, had a disturbing effect.

Since the wearable device does not give feedback on the sway direction, the effect of reducing the sway amplitude of sf and cv is not less than that of ef but very close. Johannsen et al. [JWH12] have shown through a IPLT that even an unstable reference point, in this case another person, had a reducing effect on the postural sway. For this reason, the frequency of the force of the wearable device was set at 0.3 Hz, as this corresponds to the main frequency of humans during an upright stance. Obviously the amount or the quality of the haptic information provided by the movements of the reference point at the IPLT to the own movement is decisive for the extent of the effect.

The statistical analysis of ANOVA did not show any significances between different haptic stimuli ($F(5,18)=0.961$, $p=.467$, $\eta^2=.211$). Under the conditions of the stimuli, unlike the RM in x-direction, cv had the highest mean amplitude followed by sv and sf. Since there is no scientific proof yet for the origin of trembling in the human body, only the assumption can be made at this point that the haptic stimuli supported the body in the fine adjustment around the trajectory of the RM. Whether this occurred via reflex-like reactions can only be assumed. Since the wearable device had no earth fixed reference point, stimulation by the device did not give the CNS any information about the position of the IEP. It was dependent there on the information from the other somatosensory sensors. However, the stimuli from the wearable device stimulated the mechanoreceptors pro-

cessed as reflex, since they are also connected in the spinal cord, and thus provided the activation for small-scale stabilisation of the IEP. This reasoning would make even more sense if cv also had more effect on TM in x-direction than sv and sf. Since the vibration activates the rapidly adapting sensors Ruffini corpuscle and root hair plexus, they fire at a high frequency (10-300 Hz). This high frequency could have possibly supported the fast trembling of the TM. The slow pacing Merkel cells and Meissner corpuscles could not provide sufficient information.
Since condition do of RM had no higher amplitude than the control condition, it can be assumed that the device had no irritating influences on the trembling in x-direction.
The subjects individually support the statement that all stimuli had a reducing effect. Exceptions are subject 1 which contradicts the condition sv and subject 2 which contradicts cv, which each recorded an increase compared to the cc.
For trembling in x-direction, an earth fixed reference point shows a stronger effect on sway reduction than a haptic stimulus from the wearable device.

As mentioned before, the mean values of rambling in y-direction do not allow an interpretation (see section 8.3). Descriptively, it is striking that for subjects 1, 2 and 4 all haptic stimuli have a higher value than the control condition. Likewise do shows a higher amplitude. The opposite is demonstrated by the results of subject 3, where the control condition shows the highest amplitude and a decrease of sway is to see of haptic conditions. As an scientific explanation the statement of Rabin et al. [RBDL99], that the reference point in the lateral plane has a weaker effect to the stronger sway direction than when it is in the frontal plane. This was, as already mentioned, not evaluated and it must be assumed that the y-direction was the stronger sway direction due to the bipedal Romberg's stance.

The fact that the haptic stimuli had less effect than the earth fixed reference point could be attributed to the fact that the wearable device generated almost no shear forces. Pan and Hur [PH17] have shown that the postural sway could be reduced by targeted skin stretch on the dorsal back of the hand using a wearable device. However, the balance was recorded in real time and transmitted to the subject [ibid.]. In addition, it was the subjects task to use the haptic feedback to reduce postural sway. This was different in the measurements of this work. The subjects did not know in advance what to expect and only had the task to stand still.

Both overall and for individual subjects, the inferential statistical analyses showed no significant difference between a control condition or device off with a haptic stimulus of the wearable device. Nevertheless, the descriptive analysis of the data showed tendencies indicating a slight effect of the haptic stimuli. The condition cv before sf and sv gave the impression that the effects were slightly greater in percentage terms. cv and sf even showed a lower value than the control condition in four out of five parameters, although the differences were only slight.

For this reason the third research question whether the effect of the haptic device is different among the three different stimuli conditions has to be negated and its null hypotheses is maintained. But since the sample was very small with n=4, the small effect could be elucidated with more subjects.

For the comparison of ef with a haptic device stimulus it has been shown that the earth fixed reference point has a stronger effect than a haptic device stimulus. This becomes clear because the condition ef has lower values in almost all parameters except RM in x-direction and RM in y-direction, the latter to be considered with caution. For RM in x-direction the difference is even minimal. For some subjects and parameters there are even significant differences. Therefore, I tend to say that the second research question is considered positive, even if there is no clearly significant difference. This may be due to a small sample of n=4. The alternative hypothesis of the second research question is accepted.

## 8.3 Limitations

In the previous sections was already dealt with some of the disturbing variables. This will be discussed in more detail in the following paragraphs.

**Statistics and Data Processing**
In the discussion, amplitudes of the parameters RM in x and y-direction were not compared. This is due to the fact that a peculiarity of the data recorded by the AMTI force plate was not taken into account in the data post processing, which is why an offset crept in for the calculation of the COP in y-direction.
The AMTI force plate apparently measures with a coordinate system fixed in the centre of the force plate. As soon as a force in z-axis acts on the force plate, which does not act in the centre but is shifted on the y-axis, this force generates torque around the x-axis. By the calculation of the $COP_x$ (equation 6.4), this moment shifts the COP in y-direction. Since the subjects in y-axis were not positioned in the middle of the force plate, but a little further back due to the marking for the exact foot position (see fig. 6.2 (2)), subjects with a higher body weight and consequently higher force in z-axis, had a supposedly higher amplitude. This is made clear by the figure 7.3. Subject 3 had the highest body weight of 105.6 kg followed by subject 4 of 74.9 kg, subject 1 of 68.1 kg and subject 2 of 55.6 kg.
For each subject, the offset changes only minimally as long as the subject remains in the same position on the force plate. The data can be interpreted qualitatively. If the data of different subjects are averaged, the mean value is distorted by subjects with high body weight. This distortion has no effect on TM in y-direction.

The same problem of positioning the subjects also exists in the y-axis. Since the marking on the force plate is centred and the subjects have always been in the same position, the distortion is negligible.

As already mentioned, the small sample (n=4) poses problems for statistical analysis. Thus, the normal distribution of the data for one way ANOVA was not analysed for each individual condition (n=4) using QQ plots, but across all conditions (n=24). This method is not statistically correct, but is unofficially used as an alternative. However, this method would not stand up to strict statistical control. Accordingly, the results of inferential statistics should also be viewed with caution.

Even if the results of ANOVA are not significant, it can be assumed that the condition with earth fixed reference point for individual parameters represents a significant difference. To clarify this, a t-test or the non-parametric alternative of the Wilcoxon test could have been performed between the conditions cc and ef. This would have been more likely to show a significant difference for TM in x and y-direction and for COP-velocity, but would also have had to be treated with caution due to the violation of statistical assumptions. In order for the results of the ef to remain comparable with the other conditions, it was the right decision to refer to the analysis of the ANOVA and to estimate it with the help of the descriptive analysis.

**Wearable Haptic Device**

As mentioned earlier, wearing the wearable device may have had an effect on balance. The cable connecting the device to the controlling part provided a mechanical connection to an earth fixed point. Via a chair (see fig. 6.1(C)) the cable connection was supported in such a way that the cable exerted as little force as possible on the wearable device. Only through movements of such magnitude as are not to be expected in the quiet bipedal upright stance of healthy subjects would the cable have had a haptic effect on body sway. By consistently monitoring by the supervisor, such events could be ruled out.

The pressure executed by the stamp was not completely vertical. The translatory element of the motor, which is moved by the threaded rod, was not completely fixed. It had room to move, which caused rotation around the horizontal axis until the translatory element met with resistance. This problem could have been solved by a double-sided guidance of the stamp. However, since the rotation was very small, a more complex solution was abstained.

As mentioned earlier, there were problems measuring the pressure through the FSR on the skin. Since the FSR does not measure the pressure with its entire surface but has no sensors at the edge, the measured pressure on elastic surfaces is distorted. A much greater force must be applied to measure the required force of 1 N on the skin. For this reason, the vibration motor was attached to the FSR as an intermediate piece with very thin double-sided adhesive tape to transfer the pressure into the measuring area. This force transmission may have caused a small loss of force due to the thin double-sided adhesive tape. Different values have been measured by the sensor through test measurements with a weight of 1 N. Based on this, series of measurements were taken and an average value was formed. This was defined as the limit value for 1 N.

Due to overload of the servo motor, the force of 1 N was not calculated for each sinusoidal movement, but once before each trial. The respective position of the servo motor at this force was taken as a reference position, which the motor then assumed at a rhythm of 0.3 Hz. The disadvantage of this procedure was that movements of the wearable device could increase or decrease the force applied. However, since the device was fitted with grip tape, this disturbance was very small.

Due to the computing power for the controlling part, the frequency of 0.3 Hz was not sinusoidal but linear. This could have had an influence on the quality of the perceived haptic stimulus, since human movements are generally not linear.

## 8.4 Future Work

For further work it should be tried to use the device more user centered. Since older people in particular show a significant increase in RM and TM, [ZD99] studies should be carried out to investigate the influence on this target group. It is quite possible that with more postural sway, a stronger effect may occur due to the wearable device. An effect from light touch in older people (70-79 y) will definitely occur [RWLF01]. In addition, haptic home-based balance training systems are increasingly being used successfully in rehabilitation [PH17]. They are also increasingly being worn on the wrist as a wearable device and are becoming very popular, such as wrist rotation guidance using vibration, [ASP16] or skin stretch [CPTP16]. Especially skin stretch seems to provide reliable information about the position of the body in space and guide subjects to reduce postural sway [PH17]. The difficulty of these devices, however, is that a force plate must be used to measure postural sway, since the wearable devices are still influenced by too many interfering variables, such as arm movements. Also the ergonomic design should be more in focus, as often the non-use of mobility aids is the reason for falls [Org07], and thus the inhibition threshold is lowered for the benefit of the devices. Therefore, flexible materials and designs are to be preferred for developing wearable devices and above all, they should be wireless. With 5G and better power supply, many possibilities are open, so that the devices will soon reach field tests.

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# Chapter 9

# Conclusion

In this work the influence of light touch cue provided by a wearable device and an earth fixed reference point at the wrist on the postural sway was analysed. The parameters rambling and trembling in x and y-direction as well as COP-velocity were investigated. Two female and two male (n=4) healthy young adult students were recruited as subjects. The haptic stimuli of the wearable device were constant vibration (150 Hz) with a force of $\leq$ 1 N (cv), a sinusoidal (0.3 Hz) force of $\leq$ 1 N (sf) and a sinusoidal (0.3 Hz) vibration (150 Hz) of $\leq$ 1 N (sv).

Fundamental findings were:

1. There is no significant effect of a light touch cue by the haptic device or an earth fixed reference point at the wrist depending on rambling and trembling in x and y-direction and COP-velocity.
2. An earth fixed reference point of light touch at the wrist tends to have an reducing effect on rambling in x-direction, trembling in x and y-direction and COP-velocity.
3. Individual analysis of each subject shows a significant effect on COP-velocity with mostly the condition of an earth fixed reference point as the causing effect.

In conclusion, even if the inferential statistical analysis has not shown a significant difference between cc and ef, it can be assumed that an effect exists due to the earth fixed reference point on the wrist. This is suggested by the descriptive analysis and the small sample size (n=4).
An effect due to the wearable haptic device can only be assumed, since the descriptive analysis showed tendencies. For future work, please refer to the limitations (see section 8.3). In addition, the device should be tested user centered with older adults, as the effect size of the stimuli may be larger in subjects with greater postural sway. The device should provide skin stretch and shear forces for more haptic information, different flexible materials and a wireless design should be used.

# Appendix A

# Appendix

$$V_{out} = \frac{R_M V}{(R_M + R_{FSR})}$$

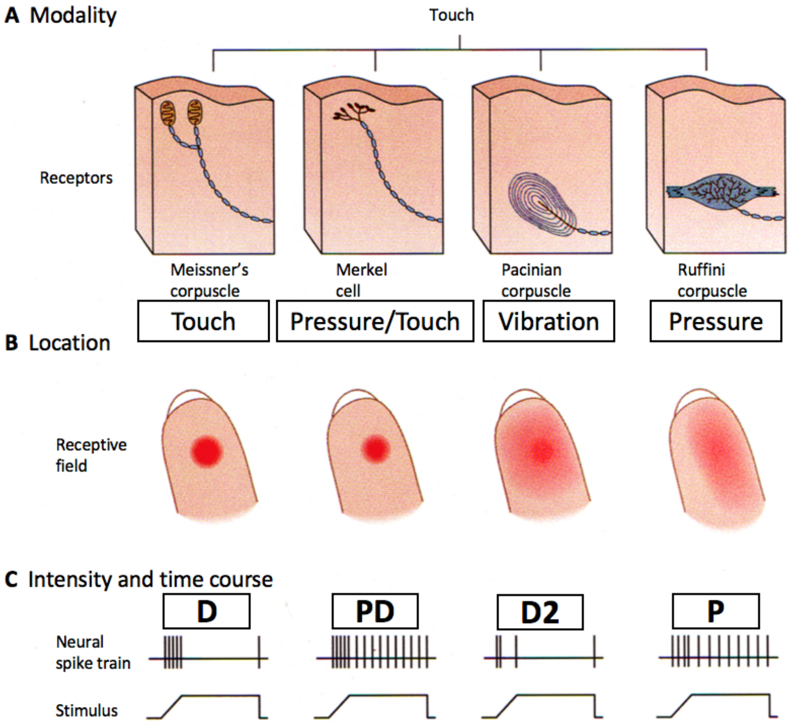

Figure A.1: The neural spike trains are (D) phasic differential, (PD) proportional differential, (D2) phasic differential and (P) tonic proportional. Figure adapted from [KSJ+12].

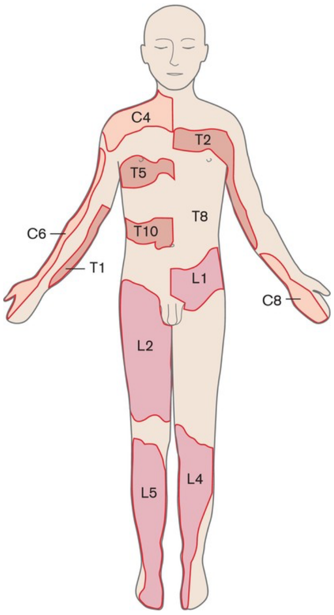

Figure A.2: Arrangement and extension of some dermatomes of the human body [PKS14].

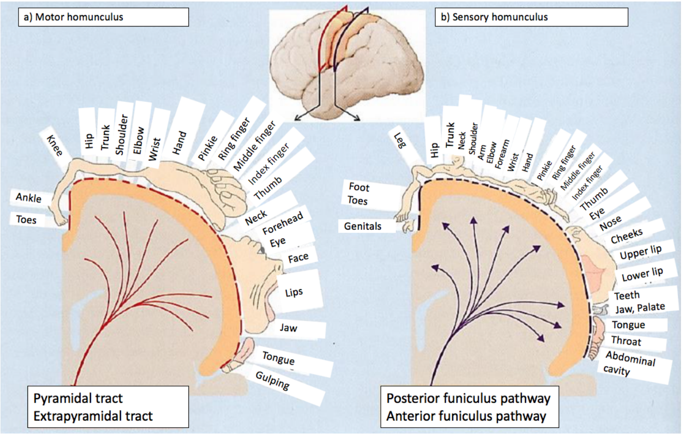

Figure A.3: Motor (a) and sensory (b) homunculus by [Lau09].

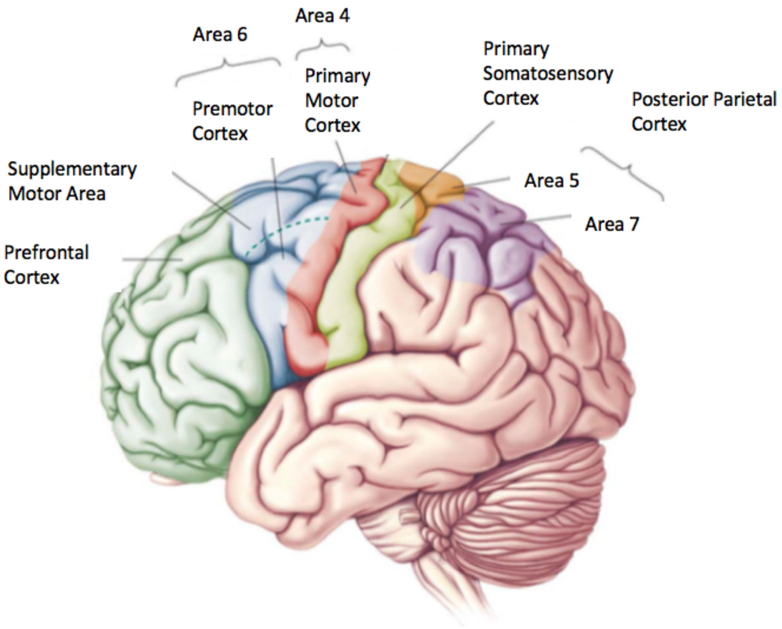

Figure A.4: Motor cortices. Fig. adapted from [BCP18].

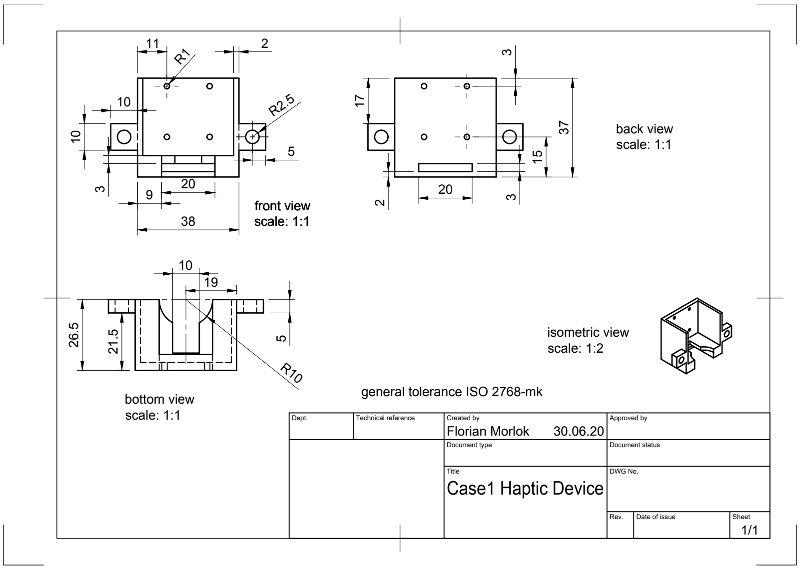

Figure A.5: Engineering drawing case haptic device part 1.

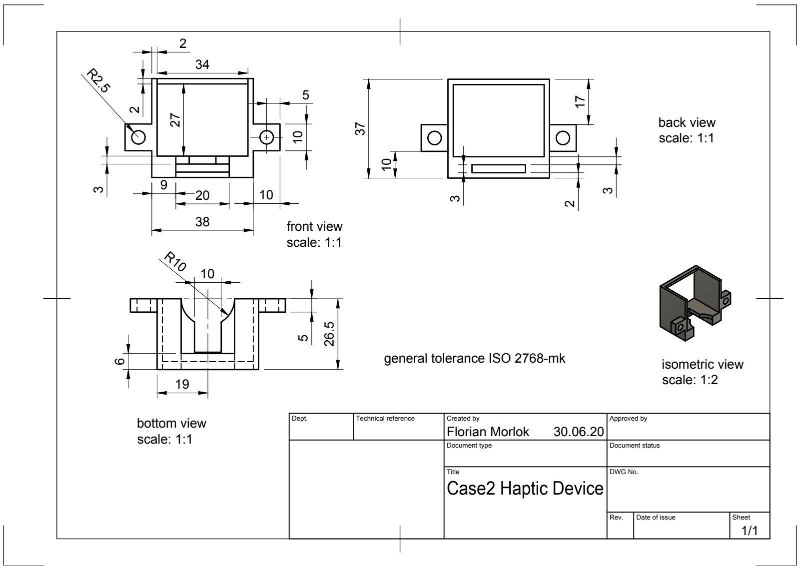

Figure A.6: Engineering drawing case haptic device part 2.

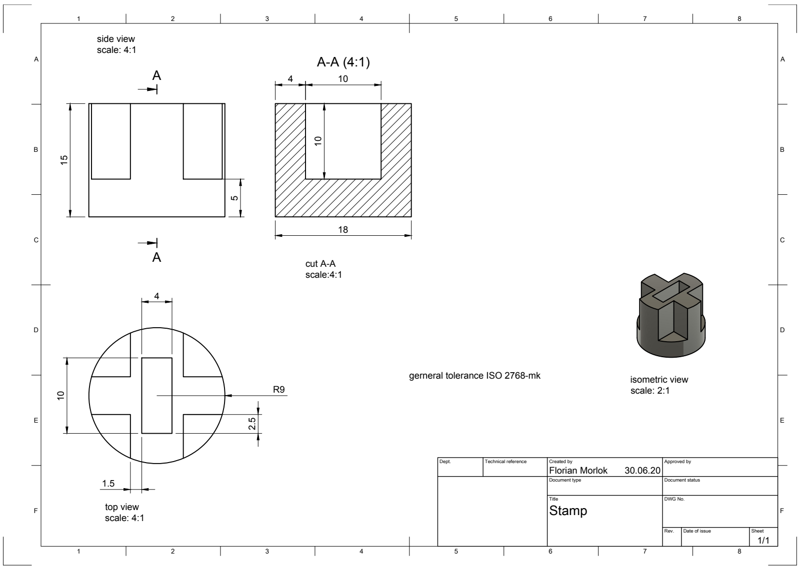

Figure A.7: Engineering drawing stamp of haptic device.

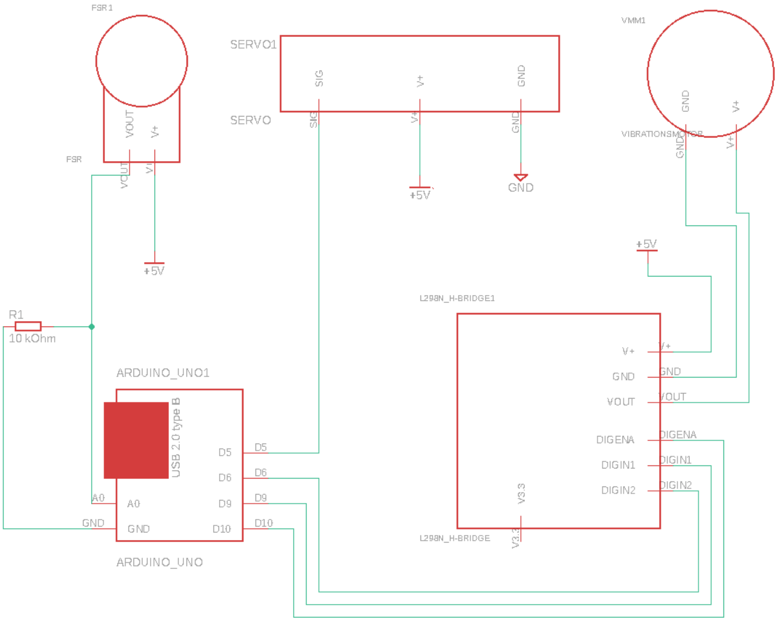

Figure A.8: The schematic of the wearable device.

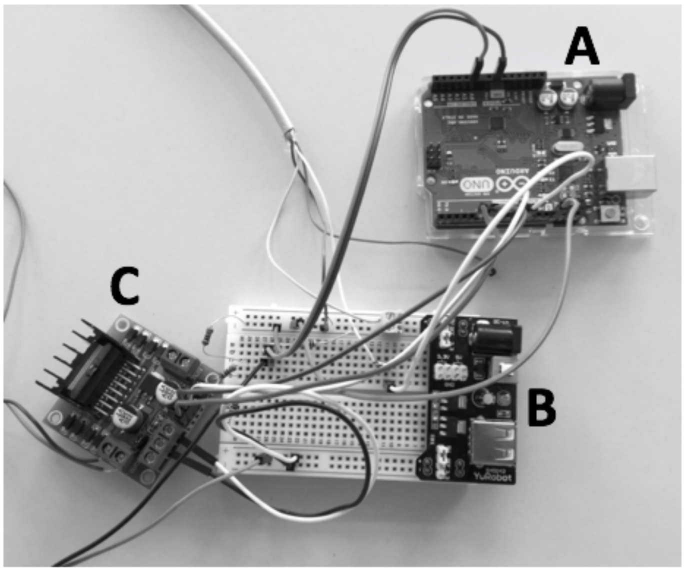

Figure A.9: (A) is the Arduino Uno, (B) power supply with breadboard and (C) the H-bridge.

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Figure A.10: Information Sheet Page 1.

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**Informationsschreiben zu folgendem Forschungsvorhaben:**

„Der Einfluss leichter Berührungsstimuli am Handgelenk auf die Körperschwankung“

Sehr geehrte Testperson,

wir bitten Sie um Ihre Teilnahme an unserer wissenschaftlichen Studie. Mit diesem Schreiben informieren wir Sie über den Zweck und Ablauf des Versuches, wie auch über die Art der Daten, die wir aufzeichnen sowie die Stimuli, die wir Ihnen präsentieren. Bitte lesen Sie die Probandeninformation sorgfältig durch. Sollten Fragen auftreten, wenden Sie sich bitte an die Studienkoordinatorin, die Ihnen diese gerne beantwortet. Die Gesamtdauer des Versuches beträgt etwa 1 Stunde. Sie können sich diese entsprechend als Versuchspersonenstunden anrechnen lassen.

Die Teilnahme an diesem Experiment ist **freiwillig** und Sie können jederzeit ohne Angaben von Gründen Ihre Teilnahme zurückziehen, vor dem Start, während, wie aber auch nach dem Experiment. Ihnen entstehen dabei keine Nachteile. Entsprechend kann auch der Versuch jederzeit abgebrochen werden, z.B. wenn Sie sich unwohl fühlen.
Sie müssen sich nicht sofort zu einer Teilnahme entscheiden. Es steht Ihnen frei, zu Hause in Ruhe darüber nachzudenken. Die Information auf den folgenden Seiten soll Ihnen bei Ihrer Entscheidung helfen.
Vorausgesetzt Sie stimmen mit den folgenden Punkten überein, wären wir Ihnen sehr dankbar, wenn Sie Ihre Einwilligung für die Teilnahme an dieser Studie geben würden.

### 1. Warum wird diese Studie durchgeführt?

Das System zur Regelung des menschlichen aufrechten Standes aus aktivem und passivem Bewegungsapparat zusammen mit dem zentralen und peripheren Nervensystem unterliegt sehr komplexen Abläufen, die noch nicht vollständig erklärt werden können.

Die Studie ist notwendig, um den Zusammenhang zwischen der Körperschwankung beim aufrechten Stand durch die Hinzunahme von verschiedenen leichten Berührungsstimulationen am Handgelenk durch einen externen Apparat zu untersuchen.
Dies dient dazu, Erkenntnisse zu gewinnen, die uns helfen ein System zu entwickeln, Personen mit Gleichgewichtsproblemen im alltäglichen Leben zu unterstützen.

### 2. Wie ist der Ablauf der Studie und was müssen Sie bei der Teilnahme beachten?

Falls nichts dagegenspricht, dass Sie an der Studie teilnehmen, werden wir zunächst ihre demographischen Daten erheben und die Fußsohlentemperatur erfassen. Im Anschluss wird Ihnen ein kleiner Apparat am Handgelenk, ähnlich einer Armbanduhr, angelegt und mit einem Klettband fixiert. Während des Tests werden wir Sie bitten für jeweils 35 Sekunden barfuß, mit beiden Füßen in einem vordefinierten Stand, ruhig auf einer Kraftmessplatte zu stehen und die Augen zu schließen. Der kleine Apparat am Handgelenk wird unterschiedliche taktile Stimuli in Form von leichtem Druck (max. 1N) und Vibration ausüben. Nach jedem Durchgang wird eine kurze Pause eingelegt. Auch können Sie uns jederzeit Bescheid geben, wenn Sie eine Pause einlegen möchten. Sie werden während der gesamten Untersuchung betreut und die Situation wird individuell angepasst.

Damit die Datenerhebung unter optimalen Bedingungen stattfindet, möchten wir Sie bitten, dass sie normale lockere Alltagskleidung tragen.

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Figure A.11: Information Sheet Page 2.

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### 3. Welchen persönlichen Nutzen haben Sie von der Teilnahme an der Studie?

Es gibt keinen unmittelbaren Nutzen für Sie durch die Studienteilnahme. Die Ergebnisse der Studie könnten jedoch dazu beitragen, dass zukünftig die Unterstützung von Personen mit Gleichgewichtsproblemen verbessert werden kann.

### 4. Welche Risiken sind mit der Teilnahme an der Studie verbunden?

Das durch die Teilnahme an der Studie verbundene Risiko ist nicht größer als beim normalen Stehen mit geschlossenen Augen. Es besteht jedoch immer das Risiko das Gleichgewicht zu verlieren, was zu Stürzen und Verletzungen, sowie Verstauchungen oder schlimmstenfalls zu Knochenbrüchen, führen kann. Wir werden jedoch alles tun, um solche Vorkommnisse zu vermeiden, indem alle unnötigen Gegenstände vor dem Beginn der Datenerhebung aus dem Weg geräumt werden, der Boden trocken gehalten wird und Sie während der Untersuchung stets die Möglichkeit haben sich festzuhalten, sollten Sie das Gleichgewicht verlieren. Sollten dennoch ernstere Komplikationen auftreten, werden wir die Messung sofort abbrechen und wenn nötig Erste Hilfe leisten. Entsprechende Ausrüstung ist bereitgestellt und ein Notruf nach medizinischer Unterstützung kann jederzeit erfolgen. Der/die Versuchsleiterin wird sich während des Versuches stets um Ihr Wohlbefinden kümmern, sowie Pausen einlegen und Ihnen Erfrischungen anbieten. Bitte informieren Sie umgehend den/die Versuchsleiter/in, falls Sie sich unwohl fühlen sollten. Der Versuch wird dann pausiert oder ganz eingestellt.

Aufgrund der COVID-19 Pandemie gelten zum Zeitpunkt der Datenerhebung die im Freistaat Bayern aufgelegten Verhaltensregeln zur Minderung der Infektionsgefahr durch das Virus SARS-CoV-2. Diesen wird in diesem Forschungsvorhaben Folge geleistet. Eine Ausnahme stellt jedoch das Anlegen des haptischen Apparates um Ihr Handgelenk bei dem der geforderte Mindestabstand von 1,5 m für ca. 30 Sekunden nicht eingehalten werden kann. Trotz des Tragens von Schutzausrüstung zur Verhinderung des Virus über die Atemwege (Mund- und Nasenschutz und Schutzhandschuhe) Ihrerseits und durch den Testleiter, weisen wir Sie auf den gegebenen Umstand hin. Mit Ihrer schriftlichen Einwilligung akzeptieren Sie das Risiko einer erhöhten Infektionswahrscheinlichkeit durch die Teilnahme an dieser Studie.

### 5. Besteht ein Versicherungsschutz?

Aufgrund des äußerst geringen Risikopotenzials der Untersuchung besteht keine Notwendigkeit für den Abschluss einer zusätzlichen Teilnehmerversicherung. Während der Untersuchung gilt durchweg die betriebliche Haftplicht der Studienstelle und im Falle einer durch die Mitarbeiter der Studienstelle nicht unmittelbar verursachten Verletzung Ihre eigene Krankenversicherung.

### 6. Wer darf an der Studie nicht teilnehmen?

Eine Teilnahme ist nicht möglich, wenn Sie nicht ohne personelle Unterstützung mit geschlossenen Augen für 35 Sekunden stehen können. Auch können Sie nicht teilnehmen, wenn Ihnen neurologische, orthopädische oder rheumatische Erkrankungen bekannt sind, die das Stehen mit geschlossenen Augen negativ beeinflussen können. Auch wenn Sie beim Stehen Schmerzen oder Schwierigkeiten haben die Anweisungen des Versuchsleiters zu befolgen, können Sie nicht teilnehmen.

Aufgrund der COVID-19 Pandemie ist eine Teilnahme nicht möglich, wenn Sie in den letzten 14 Tagen Kontakt mit Menschen hatten, die eine bestätigte Corona Virusinfektion haben, in einem vom RKI definierten Risikogebiet waren oder in der Pflege, einer Arztpraxis oder einem Krankenhaus arbeiten. Zudem ist eine Teilnahme ausgeschlossen sofern Sie unter den Symptomen Fieber (>38°C), Husten, Schnupfen, Halskratzen, Übelkeit/Erbrechen, Durchfall, Abgeschlagenheit, Gelenkschmerzen, Kopfschmerzen oder Kurzatmigkeit leiden.

Figure A.12: Information Sheet Page 3.

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### 7. Wer entscheidet, ob Sie aus der Studie ausscheiden?

Sie können jederzeit, ohne Gründe zu nennen, die Teilnahme an der Studie beenden. Es werden Ihnen dadurch keine Nachteile entstehen. Auch der Studienleiter kann die Entscheidung treffen, Sie nicht mit in die Studie aufzunehmen oder die Teilnahme vorzeitig zu beenden, wenn dies (z.B. aus medizinischen Gründen) notwendig ist.

### 8. Was geschieht mit Ihren Daten?

Während der Studie werden Angaben über Sie gesammelt und auf computerinternen, elektronischen Datenträgern (zwischen-)gespeichert. In dieser Studie ist Florian Morlok (florian.morlok@tum.de) für die Datenverarbeitung verantwortlich. Die Verarbeitung Ihrer Daten setzt Ihre Einwilligung voraus (Rechtsgrundlage). Ihre Daten werden ausschließlich im Rahmen dieser Studie verwendet. Dazu gehören personenidentifizierende Daten wie Name, Anschrift und sensible personenbezogene Gesundheitsdaten. Alle unmittelbar Ihre Person identifizierenden Daten [Name, Geburtsdatum, Anschrift, ...] werden durch einen Identifizierungscode ersetzt (pseudonymisiert). Dies schließt eine Identifizierung Ihrer Person durch Unbefugte weitgehend aus.

Ziel ist es die Ergebnisse dieser Studie möglicherweise zu veröffentlicht.
Die meisten Artikel werden über Homepage der beiden Lehrstühle (https://www.hcr.ei.tum.de/home/).

Ihre Daten werden in der Human-centered Assistive Robotics der Technischen Universität München [Prof. Dr. Dongheui Lee,dhlee@tum.de] gespeichert. Sie werden nach Ablauf von 10 Jahren / nach Ablauf der gesetzlichen Löschfristen gelöscht. Verwaltungsdaten (Name, Geburtsdatum, Adresse, E-Mailadresse) von Ihnen wie auch die Kodierliste zur Zuordnung der Studien-ID zu Ihrer Person werden nach Ablauf von 3 Jahren gelöscht.

Die Einwilligung zur Verarbeitung Ihrer Daten ist freiwillig, Sie können Ihre Einwilligung jederzeit für die Zukunft widerrufen, ohne dass die Rechtmäßigkeit der aufgrund der Einwilligung bis zum Widerruf erfolgten Verarbeitung auf Grundlage von Art. 6 Abs. 1 lit. a DSGVO berührt wird. Nach Ihrem Widerruf nehmen wir Ihre Verwaltungsdaten aus unserer Datenbank unmittelbar heraus. Ihren Widerruf richten Sie bitte an (katrin.schulleri@tum.de). Nach der Löschung der Verwaltungsdaten sowie der Kodierliste ist die Zuordnung Ihrer Person zu den Studiendaten und ein somit ein Widerruf nicht mehr möglich.

Unter den gesetzlichen Voraussetzungen besteht ein Recht auf Auskunft, sowie auf Berichtigung oder Löschung oder auf Einschränkung der Verarbeitung oder eines Widerspruchsrechts gegen die Verarbeitung sowie des Rechts auf Datenübertragbarkeit. Es besteht zudem ein Beschwerderecht beim Bayerischen Landesbeauftragten für den Datenschutz.

Bei Fragen können Sie Sich gerne an uns (florian.morlok@tum.de) oder an unseren Datenschutzbeauftragten (beauftragter@datenschutz.tum.de) wenden.

Name und Kontaktdaten des lokalen Datenschutzbeauftragten.
Prof. Dr. Uwe Baumgarten
E-Mail: beauftragter@datenschutz.tum.de
Technische Universität München
Karlstraße 45
80333 München

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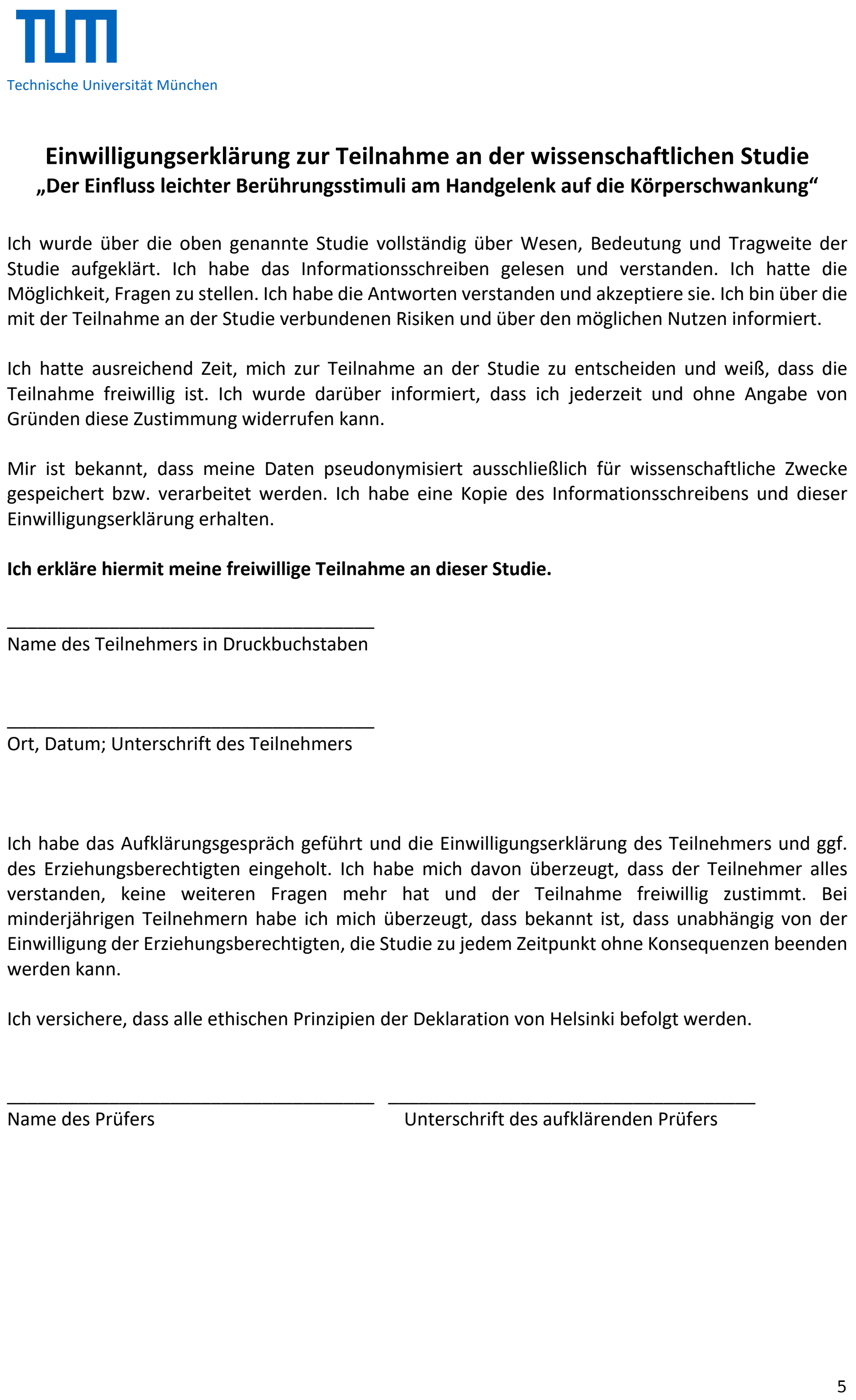
Figure A.13: Information Sheet Page 4.



Technische Universität München

**Einwilligungserklärung zur Teilnahme an der wissenschaftlichen Studie**
**„Der Einfluss leichter Berührungsstimuli am Handgelenk auf die Körperschwankung“**

Ich wurde über die oben genannte Studie vollständig über Wesen, Bedeutung und Tragweite der Studie aufgeklärt. Ich habe das Informationsschreiben gelesen und verstanden. Ich hatte die Möglichkeit, Fragen zu stellen. Ich habe die Antworten verstanden und akzeptiere sie. Ich bin über die mit der Teilnahme an der Studie verbundenen Risiken und über den möglichen Nutzen informiert.

Ich hatte ausreichend Zeit, mich zur Teilnahme an der Studie zu entscheiden und weiß, dass die Teilnahme freiwillig ist. Ich wurde darüber informiert, dass ich jederzeit und ohne Angabe von Gründen diese Zustimmung widerrufen kann.

Mir ist bekannt, dass meine Daten pseudonymisiert ausschließlich für wissenschaftliche Zwecke gespeichert bzw. verarbeitet werden. Ich habe eine Kopie des Informationsschreibens und dieser Einwilligungserklärung erhalten.

**Ich erkläre hiermit meine freiwillige Teilnahme an dieser Studie.**

______________________________________
Name des Teilnehmers in Druckbuchstaben

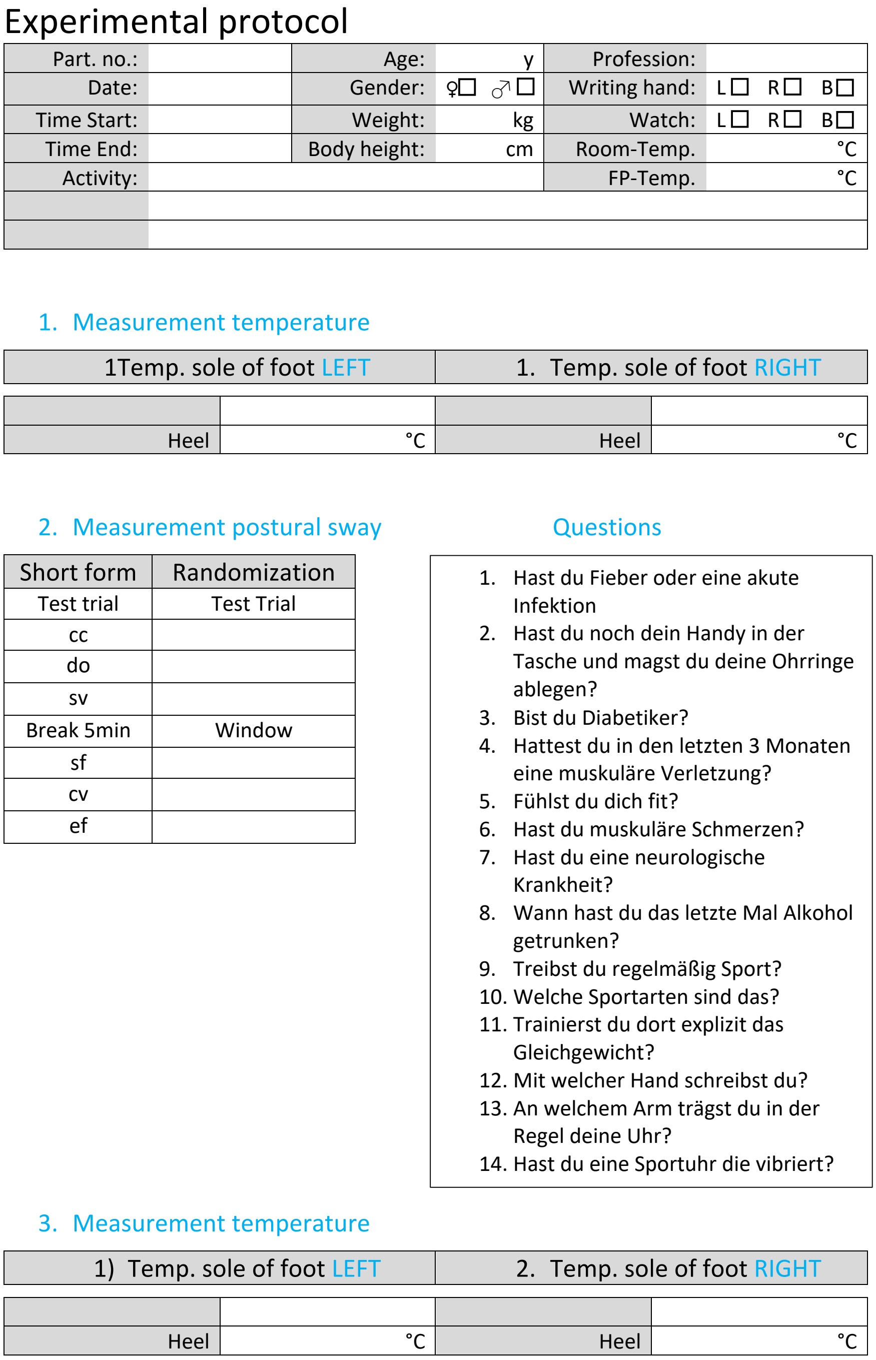
______________________________________
Ort, Datum; Unterschrift des Teilnehmers

Ich habe das Aufklärungsgespräch geführt und die Einwilligungserklärung des Teilnehmers und ggf. des Erziehungsberechtigten eingeholt. Ich habe mich davon überzeugt, dass der Teilnehmer alles verstanden, keine weiteren Fragen mehr hat und der Teilnahme freiwillig zustimmt. Bei minderjährigen Teilnehmern habe ich mich überzeugt, dass bekannt ist, dass unabhängig von der Einwilligung der Erziehungsberechtigten, die Studie zu jedem Zeitpunkt ohne Konsequenzen beenden werden kann.

Ich versichere, dass alle ethischen Prinzipien der Deklaration von Helsinki befolgt werden.

______________________________________ ______________________________________
Name des Prüfers Unterschrift des aufklärenden Prüfers

Figure A.14: Information Sheet Page 5.



## Experimental protocol

| | | | | | |
|---|---|---|---|---|---|
| Part. no.: | | Age: | y | Profession: | |
| Date: | | Gender: | ♀☐ ♂☐ | Writing hand: | L☐ R☐ B☐ |
| Time Start: | | Weight: | kg | Watch: | L☐ R☐ B☐ |
| Time End: | | Body height: | cm | Room-Temp. | °C |
| Activity: | | | | FP-Temp. | °C |
| | | | | | |
| | | | | | |

### 1. Measurement temperature

| 1Temp. sole of foot LEFT | 1. Temp. sole of foot RIGHT |
|---|---|

| | | | |
|---|---|---|---|
| | | | |
| Heel | °C | Heel | °C |

### 2. Measurement postural sway

| Short form | Randomization |
|---|---|
| Test trial | Test Trial |
| cc | |
| do | |
| sv | |
| Break 5min | Window |
| sf | |
| cv | |
| ef | |

### Questions

1. Hast du Fieber oder eine akute Infektion
2. Hast du noch dein Handy in der Tasche und magst du deine Ohrringe ablegen?
3. Bist du Diabetiker?
4. Hattest du in den letzten 3 Monaten eine muskuläre Verletzung?
5. Fühlst du dich fit?
6. Hast du muskuläre Schmerzen?
7. Hast du eine neurologische Krankheit?
8. Wann hast du das letzte Mal Alkohol getrunken?
9. Treibst du regelmäßig Sport?
10. Welche Sportarten sind das?
11. Trainierst du dort explizit das Gleichgewicht?
12. Mit welcher Hand schreibst du?
13. An welchem Arm trägst du in der Regel deine Uhr?
14. Hast du eine Sportuhr die vibriert?

### 3. Measurement temperature

| 1) Temp. sole of foot LEFT | 2. Temp. sole of foot RIGHT |
|---|---|

| | | | |
|---|---|---|---|
| | | | |
| Heel | °C | Heel | °C |

Figure A.15: Experimental Protocol.

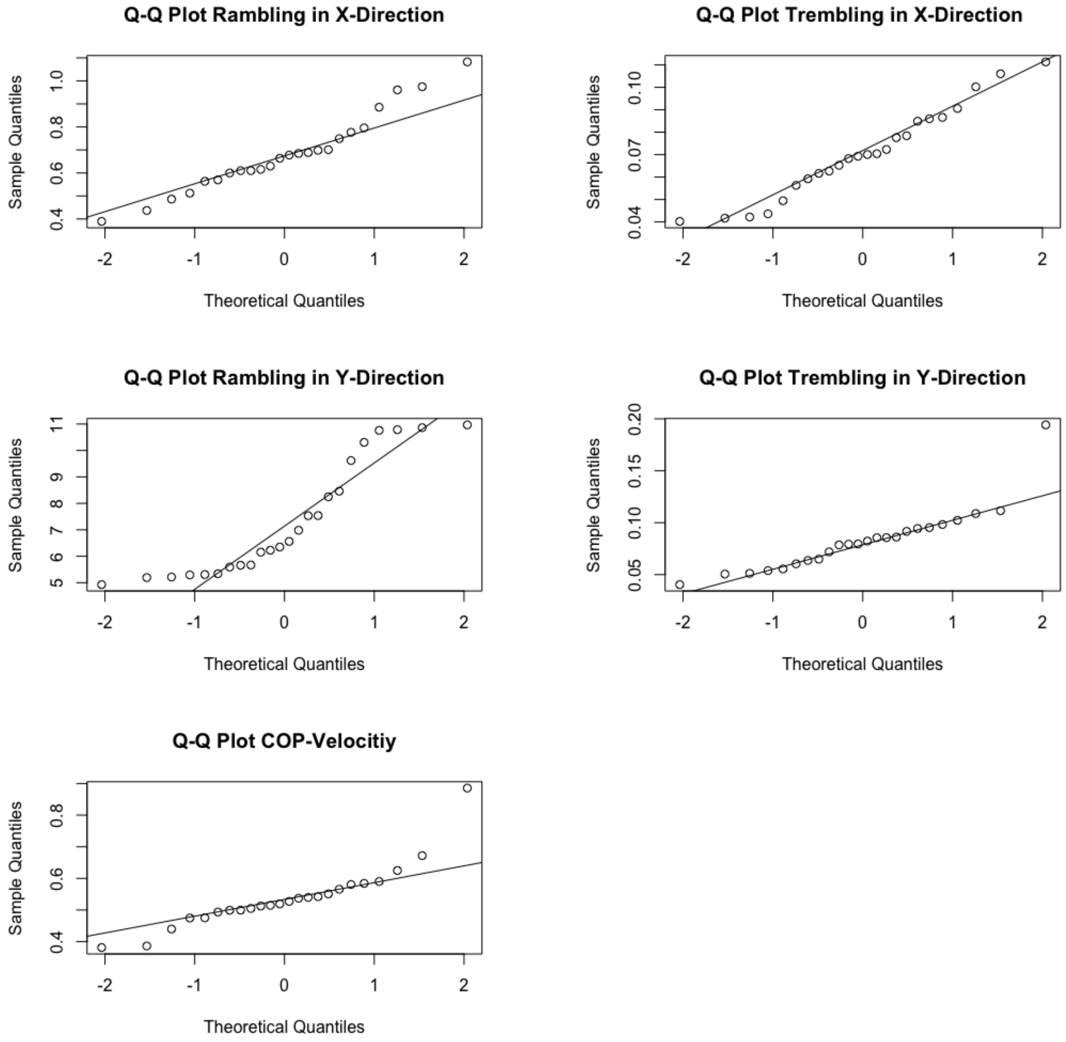


Figure A.16: QQ-Plots to test normality. Plot **top left** shows qq-plot for rambling in x-direction over all subjects and conditions. Plot **top right** shows qq-plot for trembling in x-direction over all subjects and conditions. Plot **middle left** shows qq-plot for rambling in y-direction over all subjects and conditions. Plot **middle right** shows qq-plot for trembling in y-direction over all subjects and conditions. Plot **bottom left** shows qq-plot for COP-velocity in over all subjects and conditions.

Table A.1: Mean amplitude in cm of rambling and trembling in x and y-direction and COP-velocity for all conditions control condition (cc), constant vibration (cv), device off (do), earth fixed (ef), sinusoidal force (sf) and sinusoidal vibration (sv).

| Parameter | Condition | MV | SD | Max | Min |
|---|---|---|---|---|---|
| Rambling in X-Direction | cc | 0.675 | 0.210 | 0.975 | 0.486 |
| | cv | 0.629 | 0.162 | 0.749 | 0.389 |
| | do | 0.781 | 0.219 | 1.082 | 0.564 |
| | ef | 0.619 | 0.078 | 0.688 | 0.688 |
| | sf | 0.652 | 0.187 | 0.886 | 0.437 |
| | sv | 0.736 | 0.179 | 0.961 | 0.570 |
| Trembling in X-Direction | cc | 0.081 | 0.020 | 0.106 | 0.059 |
| | cv | 0.077 | 0.029 | 0.111 | 0.042 |
| | do | 0.076 | 0.024 | 0.100 | 0.049 |
| | ef | 0.053 | 0.015 | 0.070 | 0.040 |
| | sf | 0.066 | 0.019 | 0.086 | 0.044 |
| | sv | 0.070 | 0.006 | 0.078 | 0.065 |
| Rambling in Y-Direction | cc | 6.995 | 2.682 | 10.967 | 5.194 |
| | cv | 7.108 | 2.399 | 10.306 | 4.928 |
| | do | 7.410 | 1.926 | 9.619 | 5.214 |
| | ef | 7.549 | 2.562 | 10.761 | 5.308 |
| | sf | 7.315 | 2.407 | 10.783 | 5.340 |
| | sv | 7.509 | 2.415 | 10.861 | 5.294 |
| Trembling in Y-Direction | cc | 0.084 | 0.019 | 0.102 | 0.060 |
| | cv | 0.083 | 0.026 | 0.109 | 0.051 |
| | do | 0.101 | 0.064 | 0.194 | 0.051 |
| | ef | 0.061 | 0.019 | 0.086 | 0.040 |
| | sf | 0.082 | 0.019 | 0.095 | 0.054 |
| | sv | 0.086 | 0.019 | 0.111 | 0.065 |
| COP-Velocity | cc | 0.555 | 0.031 | 0.590 | 0.515 |
| | cv | 0.548 | 0.067 | 0.625 | 0.475 |
| | do | 0.612 | 0.184 | 0.886 | 0.499 |
| | ef | 0.425 | 0.053 | 0.494 | 0.381 |
| | sf | 0.546 | 0.088 | 0.672 | 0.475 |
| | sv | 0.539 | 0.033 | 0.584 | 0.505 |

Table A.2: *Leven's Test for Homoscedasticity for parameters.*

| Parameter | Df | F-value | p-value |
|---|---|---|---|
| Rambling X | 5,18 | 0.528 | .752 |
| Trembling X | 5,18 | 2.145 | .107 |
| Rambling Y | 5,18 | 0.109 | .989 |
| Trembling Y | 5,18 | 2.501 | .069 |
| COP-velocity | 5,18 | 3.376 | .025 |

Table A.3: ANOVA *for parameters over all subjects and effect size* $\eta^2$.

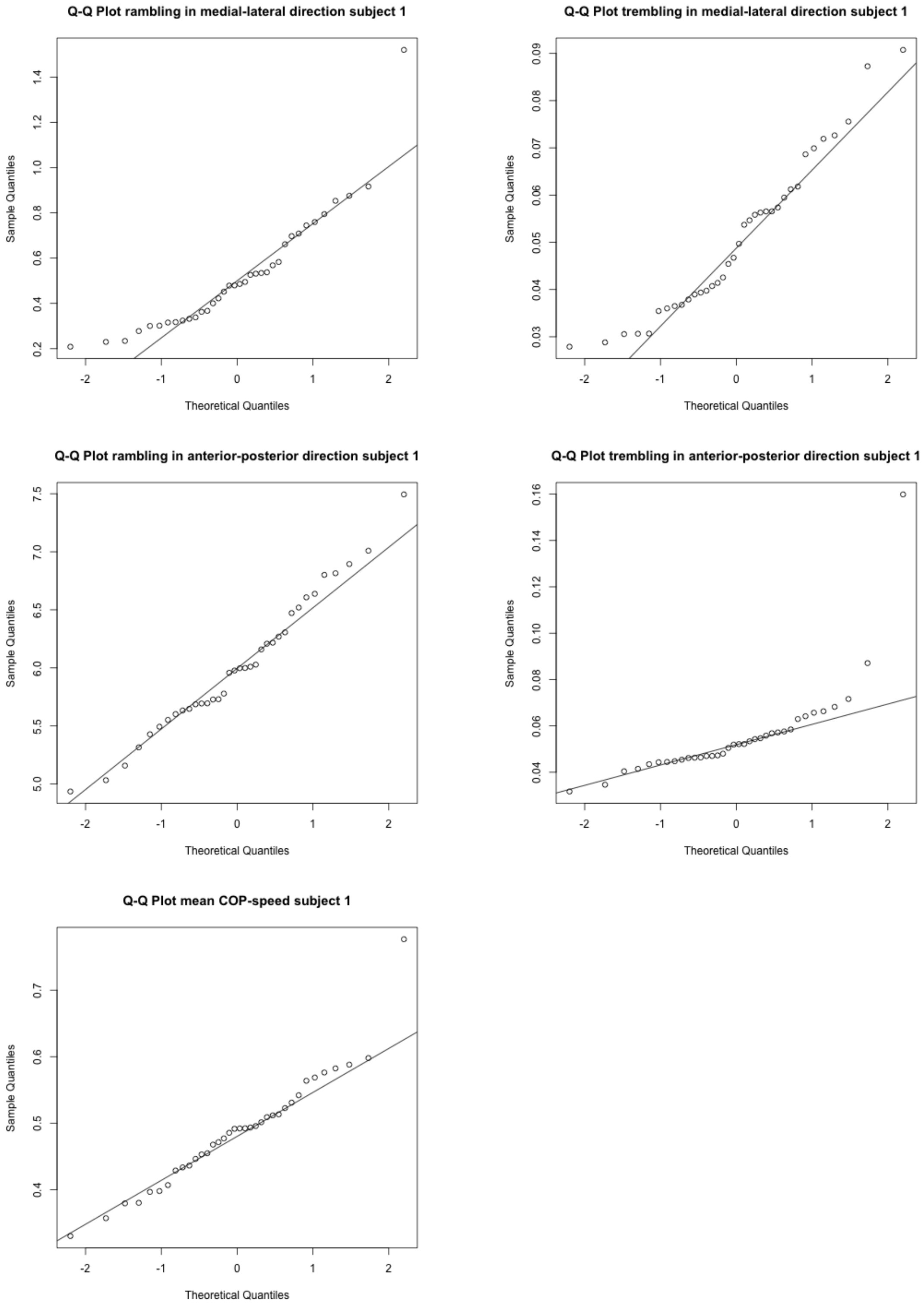
| Parameter | Df | F-value | p-value | $\eta^2$ |
|---|---|---|---|---|
| Rambling X | 5,18 | 0.513 | .763 | .125 |
| Trembling X | 5,18 | 0.961 | .467 | .211 |
| Rambling Y | 5,18 | 0.034 | .999 | .009 |
| Trembling Y | 5,18 | 0.628 | .681 | .149 |

Table A.4: Mean RMS for all subjects in cm of rambling and trembling in x and y-direction and COP-velocity for all conditions control condition (cc), constant vibration (cv), device off (do), earth fixed (ef), sinusoidal force (sf) and sinusoidal vibration (sv).

| Condition | Subject | RM x | TM x | RM y | TM y | COP-velocity |
|---|---|---|---|---|---|---|
| cc | 1 | 0.486 | 0.059 | 5.590 | 0.060 | 0.551 |
| | 2 | 0.630 | 0.106 | 5.194 | 0.094 | 0.566 |
| | 3 | 0.610 | 0.072 | 10.967 | 0.079 | 0.515 |
| | 4 | 0.975 | 0.085 | 6.228 | 0.102 | 0.590 |
| cv | 1 | 0.389 | 0.042 | 5.659 | 0.051 | 0.475 |
| | 2 | 0.698 | 0.111 | 4.928 | 0.109 | 0.625 |
| | 3 | 0.749 | 0.069 | 10.306 | 0.098 | 0.513 |
| | 4 | 0.678 | 0.087 | 7.538 | 0.072 | 0.581 |
| do | 1 | 0.564 | 0.049 | 6.560 | 0.051 | 0.499 |
| | 2 | 0.777 | 0.100 | 5.214 | 0.194 | 0.886 |
| | 3 | 0.701 | 0.063 | 9.619 | 0.079 | 0.519 |
| | 4 | 1.082 | 0.091 | 8.248 | 0.080 | 0.542 |
| ef | 1 | 0.664 | 0.042 | 5.669 | 0.040 | 0.386 |
| | 2 | 0.512 | 0.062 | 5.308 | 0.086 | 0.494 |
| | 3 | 0.688 | 0.040 | 10.761 | 0.055 | 0.381 |
| | 4 | 0.610 | 0.070 | 8.458 | 0.064 | 0.440 |
| sf | 1 | 0.437 | 0.044 | 6.155 | 0.054 | 0.475 |
| | 2 | 0.600 | 0.086 | 5.340 | 0.095 | 0.672 |
| | 3 | 0.685 | 0.056 | 10.783 | 0.092 | 0.500 |
| | 4 | 0.886 | 0.078 | 6.983 | 0.086 | 0.537 |
| sv | 1 | 0.615 | 0.068 | 6.349 | 0.065 | 0.540 |
| | 2 | 0.796 | 0.078 | 5.294 | 0.111 | 0.584 |
| | 3 | 0.570 | 0.065 | 10.861 | 0.082 | 0.527 |
| | 4 | 0.961 | 0.070 | 7.533 | 0.086 | 0.505 |

Table A.5: *Leven's Test for Homoscedasticity for each subject and parameter.*

| Subject | Value | RM x | TM x | RM y | TM y | COP-velocity |
|---|---|---|---|---|---|---|
| 1 | F-value | 3.548 | 1.585 | 1.053 | 5.048 | 2.699 |
| | p-value | .012 | .194 | .406 | .002 | .040 |
| 2 | F-value | 2.649 | 1.760 | 0.655 | 0.655 | 11.706 |
| | p-value | .043 | .152 | .660 | .660 | <.001 |
| 3 | F-value | 2.850 | 0.300 | 3.780 | 4.954 | 1.370 |
| | p-value | .032 | .909 | .009 | .002 | .264 |
| 4 | F-value | 4.302 | 1.037 | 0.298 | 3.472 | 1.427 |
| | p-value | .005 | .414 | .910 | .014 | .243 |



Q-Q Plot rambling in medial-lateral direction subject 1

Q-Q Plot trembling in medial-lateral direction subject 1

Q-Q Plot rambling in anterior-posterior direction subject 1

Q-Q Plot trembling in anterior-posterior direction subject 1

Q-Q Plot mean COP-speed subject 1

Figure A.17: QQ-Plots to test normality. Plot **top left** shows qq-plot for rambling in x-direction for subject 1 over all conditions. Plot **top right** shows qq-plot for trembling in x-direction for subject 1 over all conditions. Plot **middle left** shows qq-plot for rambling in y-direction for subject 1 over all conditions. Plot **middle right** shows qq-plot for trembling in y-direction for subject 1 over all conditions. Plot **bottom left** shows qq-plot for COP-velocity for subject 1 over all conditions.

Table A.6: Mean amplitude in cm of rambling and trembling in x and y-direction and COP-velocity for all conditions control condition (cc), constant vibration (cv), device off (do), earth fixed (ef), sinusoidal force (sf) and sinusoidal vibration (sv) of subject 1.

| Parameter | Condition | MV | SD | Max | Min |
|---|---|---|---|---|---|
| Rambling in X-Direction | cc | 0.486 | 0.049 | 0.538 | 0.400 |
| | cv | 0.389 | 0.168 | 0.661 | 0.234 |
| | do | 0.564 | 0.265 | 0.917 | 0.209 |
| | ef | 0.664 | 0.156 | 0.876 | 0.452 |
| | sf | 0.437 | 0.220 | 0.853 | 0.230 |
| | sv | 0.615 | 0.480 | 0.520 | 0.301 |
| Trembling in X-Direction | cc | 0.059 | 0.008 | 0.538 | 0.400 |
| | cv | 0.042 | 0.010 | 0.661 | 0.234 |
| | do | 0.049 | 0.013 | 0.917 | 0.209 |
| | ef | 0.042 | 0.011 | 0.876 | 0.452 |
| | sf | 0.044 | 0.016 | 0.853 | 0.230 |
| | sv | 0.068 | 0.022 | 1.520 | 0.301 |
| Rambling in Y-Direction | cc | 5.590 | 0.312 | 5.958 | 5.032 |
| | cv | 5.659 | 0.438 | 6.306 | 4.935 |
| | do | 6.560 | 0.418 | 7.009 | 5.977 |
| | ef | 5.669 | 0.331 | 6.010 | 5.158 |
| | sf | 6.155 | 0.380 | 6.608 | 5.552 |
| | sv | 6.448 | 0.729 | 7.494 | 5.315 |
| Trembling in Y-Direction | cc | 0.060 | 0.010 | 0.072 | 0.047 |
| | cv | 0.051 | 0.009 | 0.066 | 0.043 |
| | do | 0.051 | 0.005 | 0.058 | 0.046 |
| | ef | 0.040 | 0.006 | 0.045 | 0.032 |
| | sf | 0.054 | 0.006 | 0.064 | 0.046 |
| | sv | 0.077 | 0.044 | 0.160 | 0.040 |
| COP-Velocity | cc | 0.551 | 0.041 | 0.588 | 0.477 |
| | cv | 0.475 | 0.034 | 0.509 | 0.429 |
| | do | 0.499 | 0.053 | 0.582 | 0.436 |
| | ef | 0.386 | 0.040 | 0.446 | 0.330 |
| | sf | 0.475 | 0.054 | 0.542 | 0.380 |
| | sv | 0.540 | 0.134 | 0.777 | 0.398 |

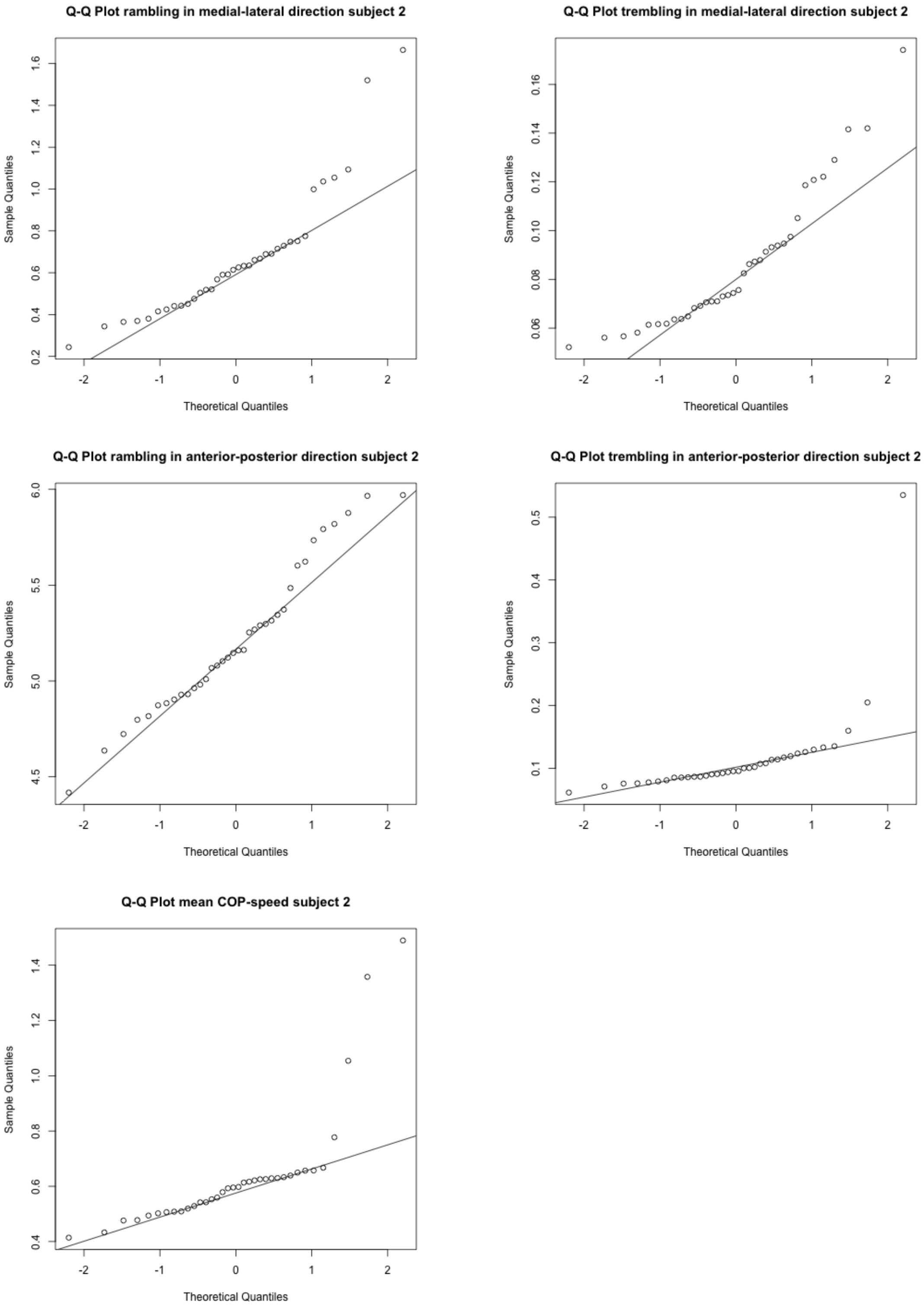


Figure A.18: QQ-Plots to test normality. Plot **top left** shows qq-plot for rambling in x-direction for subject 2 over all conditions. Plot **top right** shows qq-plot for trembling in x-direction for subject 2 over all conditions. Plot **middle left** shows qq-plot for rambling in y-direction for subject 2 over all conditions. Plot **middle right** shows qq-plot for trembling in y-direction for subject 2 over all conditions. Plot **bottom left** shows qq-plot for COP-velocity for subject 2 over all conditions.

Table A.7: Mean amplitude in cm of rambling and trembling in x and y-direction and COP-velocity for all conditions control condition (cc), constant vibration (cv), device off (do), earth fixed (ef), sinusoidal force (sf) and sinusoidal vibration (sv) of subject 2.

| Parameter | Condition | MV | SD | Max | Min |
|---|---|---|---|---|---|
| Rambling in X-Direction | cc | 0.630 | 0.157 | 0.751 | 0.369 |
| | cv | 0.677 | 0.187 | 0.999 | 0.442 |
| | do | 0.777 | 0.497 | 1.665 | 0.365 |
| | ef | 0.512 | 0.208 | 0.775 | 0.244 |
| | sf | 0.600 | 0.257 | 1.093 | 0.380 |
| | sv | 0.796 | 0.414 | 1.520 | 0.441 |
| Trembling in X-Direction | cc | 0.089 | 0.028 | 0.142 | 0.062 |
| | cv | 0.103 | 0.040 | 0.174 | 0.064 |
| | do | 0.100 | 0.032 | 0.142 | 0.061 |
| | ef | 0.062 | 0.007 | 0.074 | 0.056 |
| | sf | 0.086 | 0.021 | 0.122 | 0.065 |
| | sv | 0.078 | 0.023 | 0.119 | 0.052 |
| Rambling in Y-Direction | cc | 5.194 | 0.331 | 5.623 | 4.723 |
| | cv | 4.937 | 0.289 | 5.162 | 4.418 |
| | do | 5.214 | 0.447 | 5.877 | 4.637 |
| | ef | 5.308 | 0.455 | 5.970 | 4.817 |
| | sf | 5.340 | 0.454 | 5.966 | 4.903 |
| | sv | 5.294 | 0.341 | 5.793 | 4.963 |
| Trembling in Y-Direction | cc | 0.094 | 0.013 | 0.114 | 0.076 |
| | cv | 0.107 | 0.019 | 0.130 | 0.079 |
| | do | 0.194 | 0.172 | 0.535 | 0.090 |
| | ef | 0.086 | 0.017 | 0.107 | 0.061 |
| | sf | 0.095 | 0.018 | 0.119 | 0.071 |
| | sv | 0.111 | 0.033 | 0.160 | 0.078 |
| COP-Velocity | cc | 0.566 | 0.052 | 0.630 | 0.502 |
| | cv | 0.611 | 0.040 | 0.657 | 0.542 |
| | do | 0.886 | 0.421 | 1.489 | 0.542 |
| | ef | 0.494 | 0.065 | 0.579 | 0.414 |
| | sf | 0.672 | 0.197 | 1.054 | 0.519 |
| | sv | 0.584 | 0.115 | 0.777 | 0.478 |

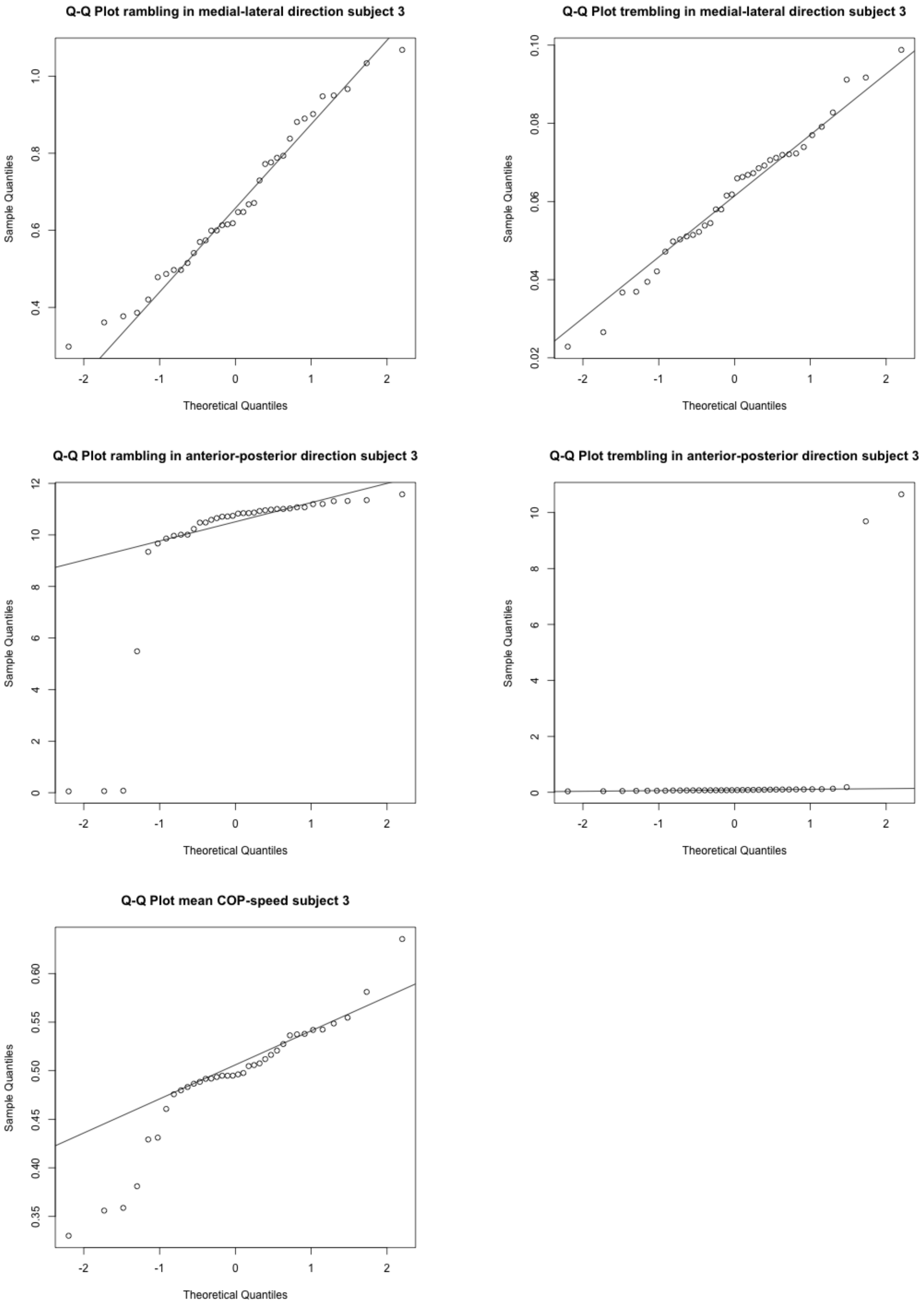


Figure A.19: QQ-Plots to test normality. Plot **top left** shows qq-plot for rambling in x-direction for subject 3 over all conditions. Plot **top right** shows qq-plot for trembling in x-direction for subject 3 over all conditions. Plot **middle left** shows qq-plot for rambling in y-direction for subject 3 over all conditions. Plot **middle right** shows qq-plot for trembling in y-direction for subject 3 over all conditions. Plot **bottom left** shows qq-plot for COP-velocity for subject 3 over all conditions.

Table A.8: Mean amplitude in cm of rambling and trembling in x and y-direction and COP-velocity for all conditions control condition (cc), constant vibration (cv), device off (do), earth fixed (ef), sinusoidal force (sf) and sinusoidal vibration (sv) of subject 3.

| Parameter | Condition | MV | SD | Max | Min |
|---|---|---|---|---|---|
| Rambling in X-Direction | cc | 0.610 | 0.253 | 1.068 | 0.361 |
| | cv | 0.749 | 0.209 | 0.966 | 0.487 |
| | do | 0.701 | 0.138 | 0.948 | 0.599 |
| | ef | 0.688 | 0.315 | 1.034 | 0.298 |
| | sf | 0.685 | 0.173 | 0.838 | 0.386 |
| | sv | 0.570 | 0.076 | 0.671 | 0.478 |
| Trembling in X-Direction | cc | 0.075 | 0.014 | 0.099 | 0.062 |
| | cv | 0.069 | 0.013 | 0.091 | 0.054 |
| | do | 0.063 | 0.012 | 0.074 | 0.042 |
| | ef | 0.040 | 0.016 | 0.067 | 0.023 |
| | sf | 0.056 | 0.016 | 0.079 | 0.039 |
| | sv | 0.065 | 0.016 | 0.092 | 0.051 |
| Rambling in Y-Direction | cc | 10.967 | 0.207 | 11.316 | 10.741 |
| | cv | 8.704 | 4.282 | 11.310 | 0.076 |
| | do | 7.854 | 4.302 | 10.650 | 0.061 |
| | ef | 10.761 | 0.754 | 11.575 | 9.345 |
| | sf | 10.783 | 0.399 | 11.349 | 10.232 |
| | sv | 9.016 | 4.411 | 11.201 | 0.052 |
| Trembling in Y-Direction | cc | 0.079 | 0.014 | 0.104 | 0.065 |
| | cv | 1.700 | 3.913 | 9.688 | 0.066 |
| | do | 1.844 | 4.315 | 10.652 | 0.056 |
| | ef | 0.055 | 0.015 | 0.074 | 0.035 |
| | sf | 0.092 | 0.027 | 0.128 | 0.054 |
| | sv | 0.082 | 0.020 | 0.100 | 0.048 |
| COP-Velocity | cc | 0.515 | 0.023 | 0.555 | 0.492 |
| | cv | 0.513 | 0.026 | 0.549 | 0.483 |
| | do | 0.519 | 0.043 | 0.581 | 0.461 |
| | ef | 0.381 | 0.041 | 0.431 | 0.330 |
| | sf | 0.500 | 0.024 | 0.537 | 0.476 |
| | sv | 0.527 | 0.056 | 0.635 | 0.492 |

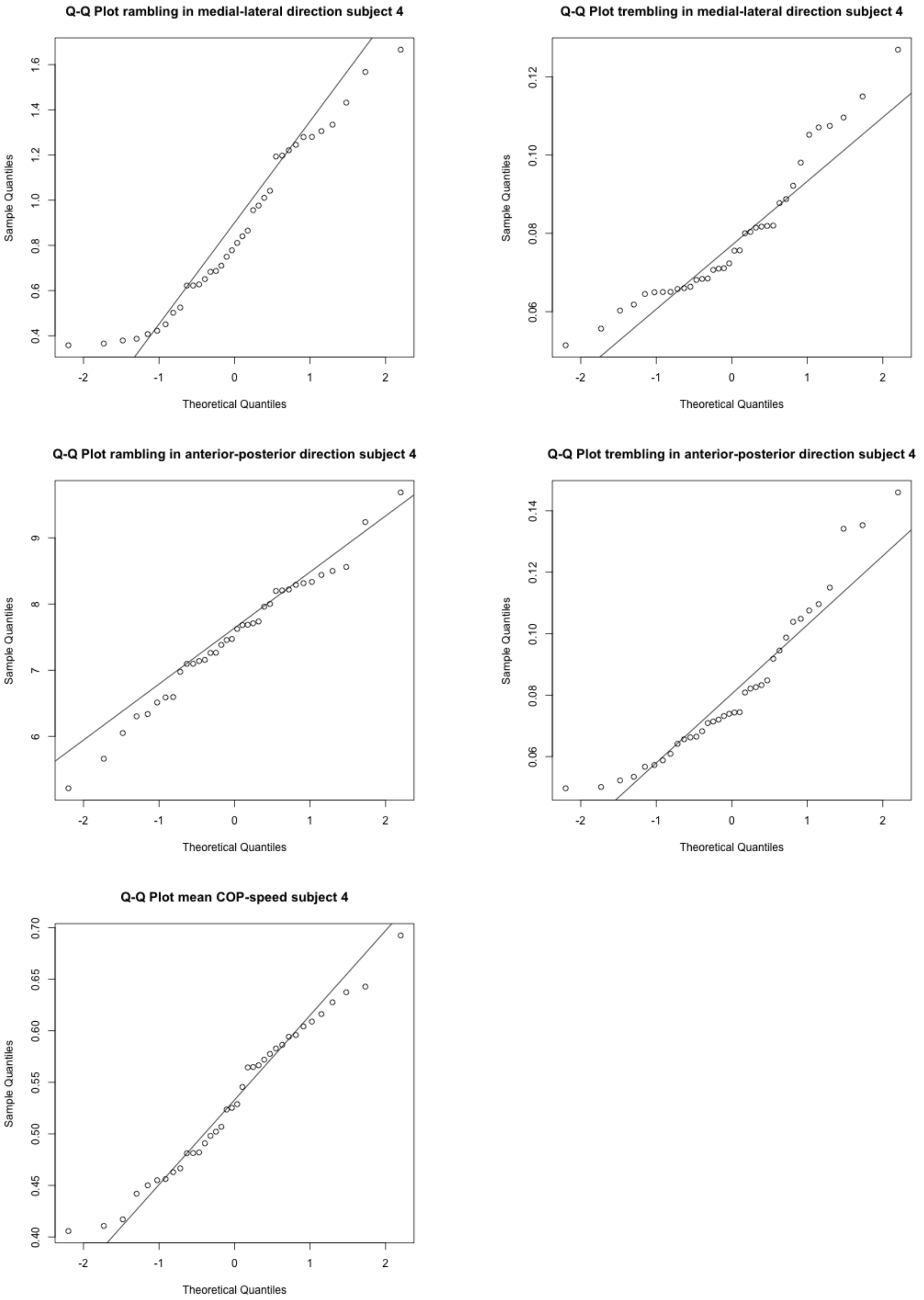


Figure A.20: QQ-Plots to test normality. Plot **top left** shows qq-plot for rambling in x-direction for subject 4 over all conditions. Plot **top right** shows qq-plot for trembling in x-direction for subject 4 over all conditions. Plot **middle left** shows qq-plot for rambling in y-direction for subject 4 over all conditions. Plot **middle right** shows qq-plot for trembling in y-direction for subject 4 over all conditions. Plot **bottom left** shows qq-plot for COP-velocity for subject 4 over all conditions.

Table A.9: Mean amplitude in cm of rambling and trembling in x and y-direction and COP-velocity for all conditions control condition (cc), constant vibration (cv), device off (do), earth fixed (ef), sinusoidal force (sf) and sinusoidal vibration (sv) of subject 4.

| Parameter | Condition | MV | SD | Max | Min |
|---|---|---|---|---|---|
| Rambling in X-Direction | cc | 0.975 | 0.336 | 1.334 | 0.622 |
| | cv | 0.678 | 0.372 | 1.245 | 0.358 |
| | do | 1.082 | 0.188 | 1.280 | 0.778 |
| | ef | 0.610 | 0.231 | 0.956 | 0.387 |
| | sf | 0.886 | 0.403 | 1.432 | 0.366 |
| | sv | 0.961 | 0.525 | 1.666 | 0.407 |
| Trembling in X-Direction | cc | 0.080 | 0.019 | 0.115 | 0.062 |
| | cv | 0.087 | 0.025 | 0.127 | 0.065 |
| | do | 0.091 | 0.017 | 0.110 | 0.071 |
| | ef | 0.070 | 0.012 | 0.088 | 0.056 |
| | sf | 0.078 | 0.016 | 0.105 | 0.065 |
| | sv | 0.070 | 0.014 | 0.092 | 0.051 |
| Rambling in Y-Direction | cc | 6.228 | 0.715 | 7.261 | 5.216 |
| | cv | 7.538 | 0.446 | 8.314 | 7.097 |
| | do | 8.248 | 0.789 | 9.686 | 7.383 |
| | ef | 8.458 | 0.498 | 9.238 | 7.682 |
| | sf | 6.983 | 0.666 | 8.001 | 6.050 |
| | sv | 7.533 | 0.582 | 8.197 | 6.594 |
| Trembling in Y-Direction | cc | 0.102 | 0.035 | 0.146 | 0.059 |
| | cv | 0.072 | 0.006 | 0.083 | 0.064 |
| | do | 0.080 | 0.020 | 0.104 | 0.050 |
| | ef | 0.064 | 0.011 | 0.081 | 0.052 |
| | sf | 0.086 | 0.028 | 0.134 | 0.053 |
| | sv | 0.086 | 0.027 | 0.115 | 0.050 |
| COP-Velocity | cc | 0.590 | 0.049 | 0.637 | 0.502 |
| | cv | 0.581 | 0.056 | 0.643 | 0.481 |
| | do | 0.542 | 0.045 | 0.604 | 0.482 |
| | ef | 0.440 | 0.035 | 0.498 | 0.406 |
| | sf | 0.537 | 0.091 | 0.692 | 0.455 |
| | sv | 0.505 | 0.051 | 0.442 | 0.442 |

Table A.10: *Tukey's post-hoc test for RM in y-direction for subject 1.*

| Condition | Diff | Lwr | Upr | p-value |
|---|---|---|---|---|
| do-cc | 0.970 | 0.165 | 1.772 | .011 |
| sv-cc | 0.858 | 0.056 | 1.660 | .030 |
| do-cv | 0.901 | 0.099 | 1.702 | .021 |
| ef-do | -0.891 | -1.692 | -0.089 | .023 |

Table A.11: *Games-Howell post-hoc test for TM in y-direction and COP-velocity for subject 1.*

| Parameter | Condition | Diff | SD | p-value |
|---|---|---|---|---|
| TM y-direction | cc-ef | 0.020 | 0.005 | .020 |
| | sf-do | 0.014 | 0.004 | .030 |
| COPvelocity | cc-ef | 0.165 | 0.025 | <.001 |
| | cv-ef | 0.089 | 0.022 | .021 |
| | do-ef | 0.113 | 0.027 | .019 |

Table A.12: *Tukey's post-hoc test for TM in x-direction and COP-velocity for subject 3.*

| Parameter | Condition | Diff | Lwr | Upr | p-value |
|---|---|---|---|---|---|
| TM x-direction | ef-cc | -0.035 | -0.060 | -0.009 | .004 |
| | ef-cv | -0.029 | -0.055 | -0.004 | .019 |
| COP-velocity | ef-cc | -0.134 | -0.200 | -0.068 | <.001 |
| | ef-cv | -0.132 | -0.198 | -0.065 | <.001 |
| | ef-do | -0.138 | -0.205 | -0.072 | <.001 |
| | sf-ef | 0.118 | 0.052 | 0.185 | <.001 |
| | sv-ef | 0.146 | 0.080 | 0.212 | <.001 |

Table A.13: *Tukey's post-hoc test for RM in y-direction and COP-velocity for subject 4.*

| Parameter | Condition | Diff | Lwr | Upr | p-value |
|---|---|---|---|---|---|
| RM y-direction | cv-cc | 1.311 | 0.208 | 2.413 | .013 |
| | do-cc | 2.020 | 0.918 | 3.122 | <.001 |
| | ef-cc | 2.231 | 1.129 | 3.333 | <.001 |
| | sv-cc | 1.305 | 0.203 | 2.407 | .013 |
| | sf-do | -1.265 | -2.367 | -0.163 | .017 |
| | sf-ef | -1.476 | -2.578 | -0.373 | .004 |
| COP-velocity | ef-cc | -0.150 | -0.201 | -0.050 | .001 |
| | ef-cv | -0.141 | -0.241 | -0.041 | .002 |
| | ef-do | -0.103 | -0.203 | -0.002 | .043 |

# List of Figures

# Acronyms and Notations

**HRC** Human-Robot Collaboration

**HRI** Human-Robot Interaction

**HRT** Human-Robot Team

**WHO** World Health Organization

**WW** Wheeled Walker

**CNS** central nervous system

**IEP** instant equilibrium point

**VSR** vestibulospinal reflexes

**CPA** compensatory postural adjustment

**COM** centre of mass

**COG** centre of gravity

**COP** centre of pressure

**EMG** electromyography

**LED** light-emitting diode

**GRF** ground reaction force

**IPLT** inter personal light touch

**JPS** joint position sense

**EPT** electrical perceptual threshold

**WBV** whole-body vibration

**SD** standard deviation

**MV** mean value

**VAR** variance

**ANOVA** analysis of variance

**RMS** root mean square

**AP** anterior-posteroir

**ML** medial-lateral

**CAD** Computer-Aided Design

**PLA** polylactide acid filament

**FSR** Force Sensing Resistor

**cc** control condition

**cv** constant vibration

**do** device off

**ef** earth fixed

**sf** sinusoidal force

**sv** suinusoidal vibration

**RM** rambling

**TM** trembling

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# Declaration

I (Florian Morlok, born on 04.09.1989) hereby affirm that I have independently written the thesis submitted by me and have not used any sources and aids other than those indicated.

München, 01.09.2020

Florian Morlok